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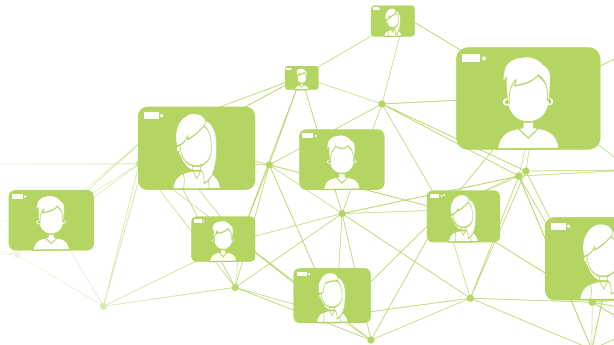
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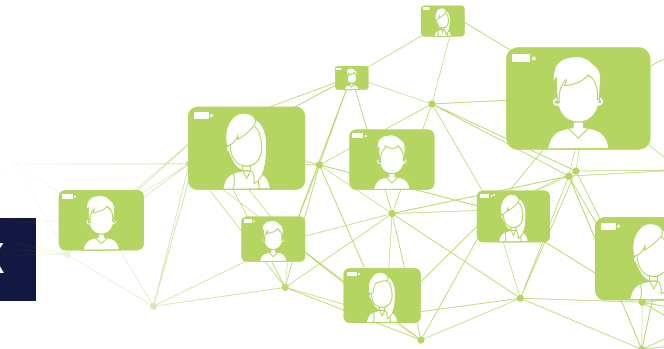
ABSTRACT E-BOOK





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TOPIC: Computational neurorehabilitation

P-101

Forward Dynamics-based Simulation Algorithm for Robotic Rehabilitation Purposes

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Robotic neurorehabilitation is a powerful resource in terms of recovering the motor skills of stroke victims. In order to develop rehabilitation robots and the interaction controls applied to these devices, the use of computational resources has increasing. However there is a need for a computational system that is both flexible and able to perform useful simulations to aid not only the development of interaction controls architectures, but also emulating the human behavior, as well as developing and analyzing interaction models. In this work we propose a forward dynamics-based algorithm that seeks to have these capabilities, being at the same time, able to support development and tuning of interaction controls, biomechanical data analysis as well as the development and evaluation of human-exoskeleton interaction models and assistive devices as orthosis and rehabilitation robots. The algorithm was developed on MATLAB using resources from libraries and models from OpenSim. Tests using experimental data from a healthy subject, 1.75 m tall, 85 kg, wearing an active right knee joint, in a seated position, performing movement of extension and flexion of the knee were conducted. In this case the active orthosis was configured in two modes: active-assistive and active-resistive. An interaction model with the same anthropometry of the subject was prepared. The collected data were inserted into the proposed algorithm in order to verify whether during the simulations the interaction model would be able to perform the same movement that the subject performed. The results obtained were satisfactory, allowing to analyze the movement and the torques from the human and the orthosis. Each simulation took about 15 minutes to be prepared and carried out. It can be concluded that the algorithm is able to reproduce data from physical experiments with precision, being a flexible and viable approach to assist in the development of resources related to robotic rehabilitation.

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TOPIC: Rehabilitation and assistive robotics

P-102

Case Study to explore the benefit of virtual reality interface combined with robotic facilitated movement to reduce supernumerary phantom limbs occurring after traumatic high-level tetraplegia (C2 AIS C)

Snow, Peter 1; Watson, Emily 2; Linley, Emma 2; Loureiro, C. V, Rui 1

1 Aspire Centre for Rehabilitation Engineering and Assistive Technology (CREATE), UCL Institute of Orthopaedics and Musculoskeletal Sciences, University College London, UK; 2 London Spinal Cord Injury Centre, Royal National Orthopaedic Hospital, UK

This case study explores the case of a female who sustained a high-level tetraplegia spinal cord injury with severe and distressing supernumerary phantom limbs and associated phantom limb pain (PLP). The level of distress, emotional burden and pain experienced were the catalyst in exploring all potential treatment avenues for this participant.

Ongoing clinical trials being carried out at the Royal National Orthopaedic Hospital (RNOH) by the Aspire Centre for Rehabilitation Engineering and Assistive Technology (CREATE) team have found a significant reduction in PLP in amputees using immersive virtual reality (VR) with robotic facilitated movements with , over 68% pain reduction (25% patients are pain free) sustained over 12 months post intervention ' [1].

The success in reducing neuropathic pain following amputation suggests that the treatment could also benefit those with PLP or other forms of neuropathic pain as a result of spinal cord injury (SCI) due to the cortical reorganisation created through the intervention. Approval was provided by the hospitals Surgical Innovation and New Techniques and Technology (SINTT) committee for this SCI individual to receive the combined VR and robotic intervention (which at present is at research phase) as all other traditional interventions had been unsuccessful in offering any relief. It was anticipated that results with the first SCI participant would mirror the amputee research trials with a reduction in PLP and neuropathic pain. With this anticipation the individual received the prescribed nine sessions [1] of the intervention over a two and a half week period. This was done while the participant remained an inpatient receiving their first episode of care in the London Spinal Cord Injury Centre (LSCIC). This approach negated any consumables and other costs that would otherwise have been required and allowed participation that would have been impossible to deliver in an outpatient setting.

References: Snow, P. W., Sedki, I., Sinisi, M., Comley, R., & Loureiro, R. C. V. (2017). Robotic therapy for phantom limb pain in upper limb amputees. 2017 International Conference on Rehabilitation Robotics (ICORR). IEEE. doi:10.1109/ICORR.2017.8009383

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TOPIC: Human-machine interfaces in rehabilitation

P-103

Extracting Human-Robot Interaction Torque Based on A Novel Cable-Driven Upper-Limb Exoskeleton Equipped with Torque Sensors

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Powered exoskeletons have global trends in broad application fields such as rehabilitation and human strength amplification in industry, military, and activities in daily livings. Physical human-machine interface based on interaction force is a major method to obtain the wear-er's motion intention. Usually, the subject is required to hold the grip attached to the 6-axis force sensor to apply human force, which limits the human-exoskeleton interaction mode and hinders the motor-sensory function of the human hand. Therefore, the torque sensor is selected to detect the human upper limb motion intension at the first time as far as we know. It can measure the interaction force of any contact point on the robotic arm and detect the sum of the multi-point interaction forces applied at different contact points simultaneously. The model of torque sensor signal is established for a portable upper limb exoskeleton named PBIE. However, the torque sensor signals include not only the active joint torque of subjects, but also undesired torque components, such as friction torque. To accurately de-couple the torque sensor signal, a nonlinear numerical friction model is established based on LuGre friction model. A protocol for parameter identification of the proposed friction model is proposed and verified by experiment. Furthermore, for the backlash and hysteresis characteristics of bidirectional cable drive, a coefficient for the combination of two friction models for antagonistic directions in a joint is designed. Owing to this coefficient, the error of the friction model is reduced by about 90% when the motion direction changes. Finally, the ac-curacy of the torque sensor model is verified by experiments, and the RMSE is about 0.033 Nm (2.5%). The MAE of extracted interaction torque is about 0.3 Nm (7.5%). This paper potentially promotes the research on intuitive control of exoskeleton and the development of the upper-limb exoskeleton for active rehabilitation and assistance.

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TOPIC: Rehabilitation and assistive robotics

P-104

Rehabilitation and Cortical Remodeling After Surgical Intervention for Spinal Cord Injury

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The recovery of hand and arm function is the highest priority for tetraplegic individuals living with chronic spinal cord injury (SCI) as it is critical for decreasing long-term care costs and increasing quality of life. Nerve transfer surgery leverages the intrinsic regenerative capacity of peripheral axons to create a novel circuit to bypass the level of injury without significantly sacrificing spared function. Intact donor nerves from above the level of injury are coapted to recipient nerves arising at or below SCI. Recovery can be highly variable and there is a need to determine the effectiveness of rehabilitation in supporting recovery of function and the motor networks that underlie that function. The objective is to determine the capacity for cortical motor networks to incorporate novel nerve transfer circuits through intensive robotic rehabilitation. The hypothesis is that nerve transfer surgery after cervical SCI creates a novel cortical motor network, supporting the return of function through rehabilitation-dependent remodeling. Longitudinal transcranial magnetic stimulation (TMS) mapping and functional evaluations will be used to determine mechanisms that support rehabilitation-mediated recovery after nerve transfer. Preliminary baseline evaluations of 6 patients (mean = 94 months post-SCI) have shown that baseline upper extremity is concentrated in the biceps and elbow, with virtually no hand function. Initial TMS maps confirm these clinical and kinematic findings. The expectation is to determine the role for rehabilitation in supporting recovery of hand and arm function after nerve transfer and in shaping cortical control of a novel, functional forelimb circuit. These findings will have an impact on the current state of clinical knowledge and provide targets for improving nerve transfer and maximizing recovery of hand and arm function after SCI.

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TOPIC: Rehabilitation and assistive robotics

P-105

The Myoshirt: A Textile Exomuscle That Assists the Shoulder in Everyday Life

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In the treatment of upper limb impairments, rehabilitation and assistive robots are promising tools for regaining function. While various devices for rehabilitation training have found their way into hospitals and therapy practices, to date, standard approaches for assisting the upper limb outside the clinical environment are unavailable.

To address this gap, we developed the Myoshirt, a textile soft wearable robot, or exomuscle, that assisted the shoulder on a one-dimensional, functionally coupled movement path. Through the implementation of an intuitive, indirect force controller, the Myoshirt compensated for 70% of the forces acting on the shoulder due to gravity, while autonomously moving in concert with the user.

In this study, participants without impairments ($n=10$, 5 male) were able to raise an external load significantly longer by an average of 51.1 s (36.1%) when wearing the Myoshirt compared to the baseline without the device, and significantly reduced their muscular activity by up to 49.1% when lifting weights to different shelf heights. Though wearing the Myoshirt significantly reduced their range of motion, participants were able to cover the workspace required for activities of daily living in both conditions. In a subsequent case study, two participants with upper limb impairments due to a muscular dystrophy and a spinal cord injury were able to raise their unloaded arms substantially longer by 256.4 s (61.5%) and 450.6 s (210.3%), respectively, when wearing the Myoshirt compared to the baseline. At the same time, their perceived exertion decreased on the Borg Scale from 18 to 6 and from 18 to 15 points, respectively.

The Myoshirt proved to be an intuitive tool that functionally assisted the shoulder in daily life-like tasks. In the future, devices like the Myoshirt may enhance clinical and home-based therapy, provide assistance during activities of daily living, and thereby increase the personal independence of people with upper limb impairments.

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et al., "Soft Robotic Suits: State of the Art, Core Technologies, and Open Challenges," in IEEE Transactions on Robotics, doi: 10.1109/TRO.2021.3084466.

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TOPIC: Wearable devices

P-106

Wearable Devices for Biofeedback Rehabilitation: A Systematic Review and Meta-Analysis to Design Application Rules and Estimate the Effectiveness on Balance and Gait Outcomes in Neurological Diseases

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Wearable devices are used in rehabilitation to provide biofeedback about biomechanical

or physiological body parameters to improve outcomes in people with neurological diseases. This is a promising approach that influences motor learning and patients' engagement. Nevertheless, it is not yet clear what the most commonly used sensor configurations are, and it is also not clear which biofeedback components are used for which pathology. To explore these aspects and estimate the effectiveness of wearable device biofeedback rehabilitation on balance and gait, we conducted a systematic review by electronic search on MEDLINE, PubMed, Web of Science, PEDro, and the Cochrane CENTRAL from inception to January 2020. Nineteen randomized controlled trials were

included (Parkinson's n = 6; stroke n = 13; mild cognitive impairment n = 1). Wearable devices mostly provided real-time biofeedback during exercise, using biomechanical sensors and a positive reinforcement feedback strategy through auditory or visual modes. Some notable points that could be improved were identified in the included studies; these were helpful in providing practical design rules to maximize the prospective of wearable device biofeedback rehabilitation. Due to the current quality of the literature, it was not possible to achieve firm conclusions about the effectiveness of wearable device biofeedback rehabilitation. However, wearable device biofeedback rehabilitation seems to provide positive effects on dynamic balance and gait for PwND, but higher-quality RCTs with larger sample sizes are needed for stronger conclusions.

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TOPIC: Human-machine interfaces in rehabilitation

P-107

An Adaptive Filter for Low-Tolerance SEMG-Based Intention Prediction

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Myocontrol based upon machine learning (ML) relies on the stability and repeatability of signals related to muscular activity. However, ML algorithms typically employed in myocontrol are prone to several issues, which can make them non-viable in certain applications with low tolerances for delays and prediction instability, such as exoskeleton control or teleimpedance. These issues can become dramatic whenever, e.g., muscular activity is present not only when the user is trying to move, but also for mere gravity compensation, which is generally the case the more proximal a muscle is. The shoulder muscles, for instance, have to be activated to compensate for gravity in a far greater measure than, for example, the M. Flexor Digitorum Superficialis, and a substantial part of this instability is to be attributed to the inherent heteroscedasticity of the sEMG signal.

In this study we introduce and characterize an adaptive filter for sEMG-based motion intention prediction to be used in such situations, which automatically adjusts its own cutoff frequency to suit the current movement intention. This filter generally shows better behavior with regards to delay than a standard low-pass filter while providing much more stability during isometric contractions or co-contractions and less overshoot during, e.g., the lifting of a weight.

References: Gijsberts, A., Bohra, R., Sierra Gonzalez, D., Werner, A., Nowak, M., Caputo, B., ... & Castellini, C. (2014). Stable myoelectric control of a hand prosthesis using non-linear incremental learning. *Frontiers in neurorobotics*, 8, 8.

This work was supported by: German Aerospace Center

ABSTRACT

Myocontrol based upon machine learning (ML) relies on the stability and repeatability of signals related to muscular activity. However, ML algorithms typically employed in myocontrol are prone to several issues, which can make them non-viable in certain applications with low tolerances for delays and prediction instability, such as exoskeleton control or teleimpedance. These issues can become dramatic whenever, e.g., muscular activity is present not only when the user is trying to move, but also for mere gravity compensation, which is generally the case the more proximal a muscle is. The shoulder muscles, for instance, have to be activated to compensate for gravity in a far greater measure than, for example, the M. Flexor Digitorum Superficialis, and a substantial part of this instability is to be attributed to the inherent heteroscedasticity of the sEMG signal. In this study we introduce and characterize an adaptive filter for sEMG to be used in such situations, which automatically adjusts its own cutoff frequency to suit the current movement intention. This filter generally shows better behavior with regards to delay than a standard low-pass filter while providing much more stability during isometric contractions or co-contractions and less overshoot during, e.g., the lifting of a weight.

Keywords: sEMG, biosignals, heteroscedasticity, adaptive filtering.

INTRODUCTION

The adaptive filter consists of a single pole IIR discrete lowpass filter, which automatically sets its own cutoff frequency F_c based on the magnitude of the input signal $x(t)$ and of its first time derivative $\dot{x}(t)$, according to the following equations.

$$F_c = \exp(G2 \cdot |x(t)| + G1 \cdot LP(|\dot{x}(t)|, B1) + B2) \quad \text{with cutoff frequency } F_c \text{ and input signal } x$$

$$\alpha = \frac{2\pi F_c T_s}{1 + 2\pi F_c T_s} \quad \alpha \text{ being the filter's decay coefficient, and } T_s \text{ being the sampling period}$$

$$y_i = \alpha x_i + (1 - \alpha)y_{i-1} \quad y_i \text{ being the time-discretized signal } y$$

In the above equations, $LP(x(t), F_c)$ indicates the output at time t of a lowpass filter with input $x(t)$ and cutoff frequency F_c . The filter was applied to the output of a ridge regression converting 8 sEMG envelopes ($F_s = 200$ Hz, LP filter $F_c = 1$ Hz 2nd order Butterworth) using a *Myo* bracelet from *Thalmic Labs* to a prediction of the muscle torque along the elbow axis. Figure 1 shows the user training the ridge regression with a dumbbell. The training consisted in performing a 30 s isometric contraction and 10 repetitions raising the dumbbell. The procedure was repeated 6 times for two weights (2 kg and 10 kg).

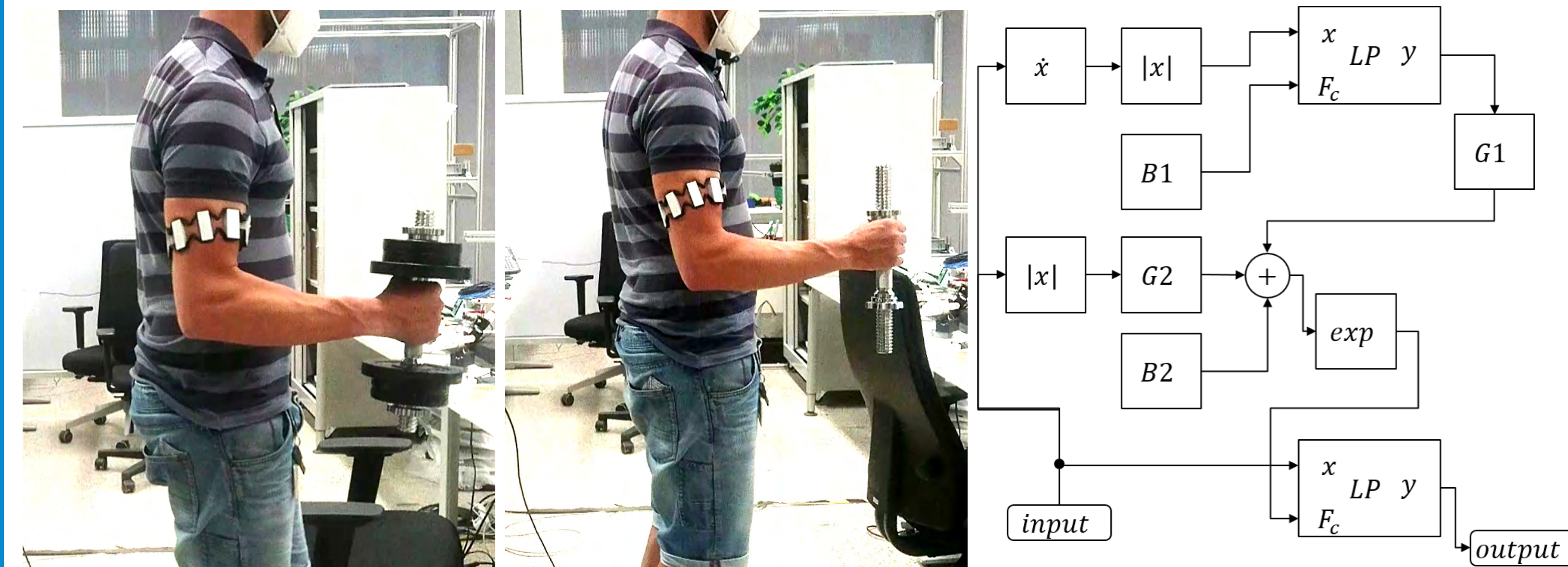


Figure 1: Left: User with sEMG sensor raising the heavy and the light weight. Right: Block diagram of the adaptive filter.

RESULTS

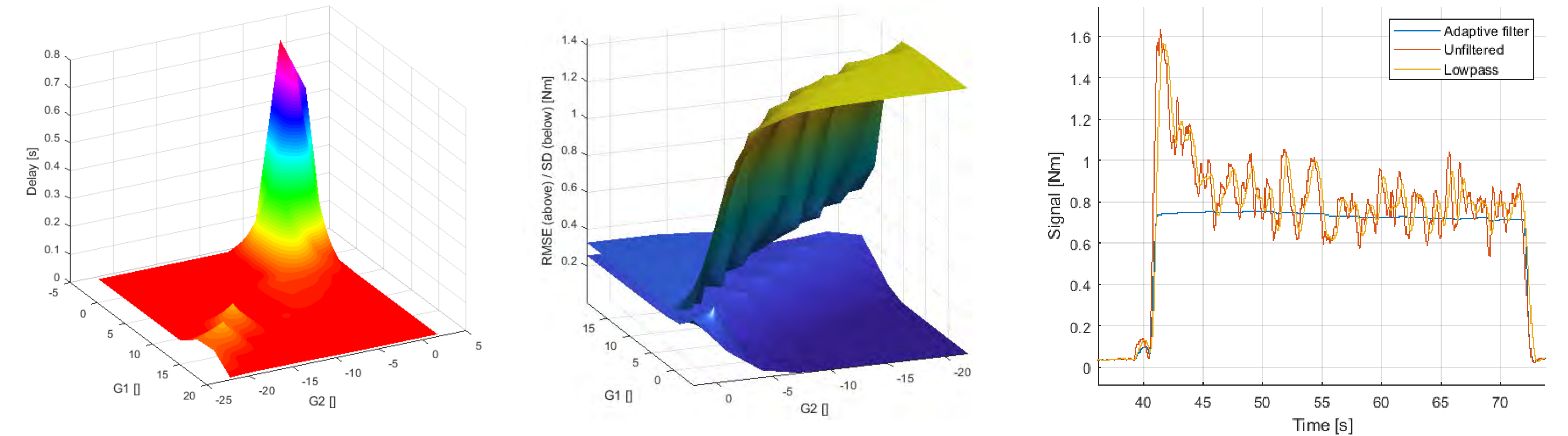


Figure 2: **Left:** empirically measured signal delay values over the corresponding G1 and G2 coefficient values for the isometric contraction task. **Center:** empirically measured RMSE (upper surface) and standard deviation (lower surface) of the adaptive filter output over the corresponding G1 and G2 coefficients for the isometric contraction task. **Right:** Representative comparison between the unfiltered signal, the adaptive filter output and a low-pass filter.

Table 1 shows the most significant results of the paired t-test on the experimental data ordered by experimental conditions. Unless otherwise specified, the adaptive filter's coefficients were tuned to $G1 = 7.5$; $G2 = -4$; $B1 = -1$; $B2 = 0.3$.

Metric [Unit]	Adaptive filter	Low-pass filter	Significant effects and notes
Delay [s]	0.0067 (0.0133)	0.1602 (0.0627)	$t(23) = 12.2254$; $p < 0.005$, all tasks
SD [Nm]	0.5168 (0.1520)	0.5801 (0.1991)	$t(11) = 2.6123$; $p < 0.05$, weightlifting task
SD [Nm]	0.2280 (0.0927)	0.2682 (0.1260)	$t(11) = 3.6589$; $p < 0.05$ isometric contraction
RMSE [Nm]	0.2945 (0.0503)	0.3365 (0.0904)	$t(11) = 2.9429$; $p < 0.05$, isometric contraction

Table 1: Result Overview: means and standard deviations (in parentheses) for all experimental conditions and significant effects.

CONCLUSIONS

- The adaptive filter shows a significantly lower delay compared to the low-pass filter (see Fig. 2 left).
- The fact that the adaptive filter output shows a lower standard deviation compared to the low-pass filter's indicates less overshoot overall during the weightlifting task.
- While a low root mean square error (RMSE) and a low standard deviation during a prolonged isometric contraction are a trade-off in the absence of feedback (see Fig. 2 center), the filter shows significantly lower RMSE and standard deviation than the low-pass filter during isometric contractions.
- The lower standard deviation of the adaptive filter output during the isometric task indicates a more constant signal in spite of the inherent sEMG noise during contraction (see Fig. 2 right).
- Furthermore, in the presence of feedback, the user should easily be able to reach a desired output level and then maintain it with very low noise, as shown in Figure 2 right.

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TOPIC: Wearable devices

P-108

An SEMS-Based Force Feedback Device for Teleoperation and Rehabilitation.

Sierotowicz, Marek 1, 2; Claudio Castellini 1, 2

1: Friedrich-Alexander University, Erlangen; 2: German Aerospace Center, Wessling, Germany

Electrical Muscular Stimulation (EMS) is a promising tool for scenarios where force feedback is required either with the goal of causing a movement in a user with impaired motor control or of providing haptic cues to a healthy user in, e.g., teleoperation or applications in virtual reality. An EMS system can be much more energy efficient than an exoskeleton, and can furthermore preserve muscular activity in users unable to voluntarily move. In rehabilitation, per- or subcutaneous electrodes are often the preferred solution if precision and selectiveness have priority. However, if surgical implantation is undesirable, surface electrodes can also be used. These are, however, subject to many issues with regard to the precision attainable when stimulating a given muscle group. Because of the distance from inner muscles and the presence of fat/connective tissue, surface EMS (sEMS) can lead to the unwanted stimulation of untargeted motor neurons. Furthermore, when using surface electrodes it is impossible to individually stimulate deeper muscle groups without also stimulating the superficial ones. Moreover, most solutions known from literature seem to address very specific joint movements.

In this article we introduce the MyoCeption: a wearable, wireless sEMS-based force feedback device able to provide stimulation currents on up to 10 independent channels with 16-bit amplitude resolution. This stimulation is computed by a piece of proprietary software based on the current pose of the user applied to a real-time musculoskeletal model and impedance control, which can be tuned via twitch-based calibration. This technique consists in passing a sharp stimulation signal across an individual electrode pair and measuring the angular velocity of the consequent twitch in direction and magnitude. Based on this technique the system calibrates its own musculoskeletal model, as well as the weights modulating the intensity of the stimulation applied to each electrode pair.

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ABSTRACT

Electrical Muscular Stimulation (EMS) is a promising tool for scenarios where force feedback is required either with the goal of causing a movement in a user with impaired motor control or of providing haptic feedback to a healthy user in, e.g., teleoperation or applications in virtual reality. An EMS system can be much more energy efficient than an exoskeleton, and can furthermore preserve muscular activity in users with impaired motor control. In rehabilitation, per- or subcutaneous electrodes are often the preferred solution if precision and selectiveness have priority. However, if surgical implantation is undesirable, surface electrodes can also be used. These are, however, subject to many issues with regard to the precision attainable when stimulating a given muscle group. Because of the distance from inner muscles and the presence of fat/connective tissue, surface EMS (sEMS) can lead to the unwanted stimulation of untargeted motor neurons. Furthermore, when using surface electrodes it is impossible to individually stimulate deeper muscle groups without also stimulating the superficial ones. Moreover, most solutions known from literature seem to address very specific joint movements. In this article we introduce the MyoCeption: a wearable, wireless sEMS-based force feedback device able to provide stimulation currents on up to 10 independent channels with 16-bit amplitude resolution. This stimulation is computed by a piece of proprietary software based on the current pose of the user applied to a real-time musculoskeletal model and impedance control, which can be tuned via twitch-based calibration. This technique consists in passing a sharp stimulation signal across an individual electrode pair and measuring the angular velocity of the consequent twitch in direction and magnitude. Based on this technique the system calibrates its own musculoskeletal model, as well as the weights modulating the intensity of the stimulation applied by each single electrode pair.

Keywords: EMS, force feedback, wearable, rehabilitation.

INTRODUCTION

The MyoCeption in this experiment was used in conjunction with the BodyRig, an IMU-based body tracking system. Figure 1 shows the full setup as well as a detailed breakdown of the MyoCeption. The system is able to operate an automatic calibration of the underlying musculoskeletal model by probing the reaction of the user to a sharp stimulation current (see Fig. 2 right).

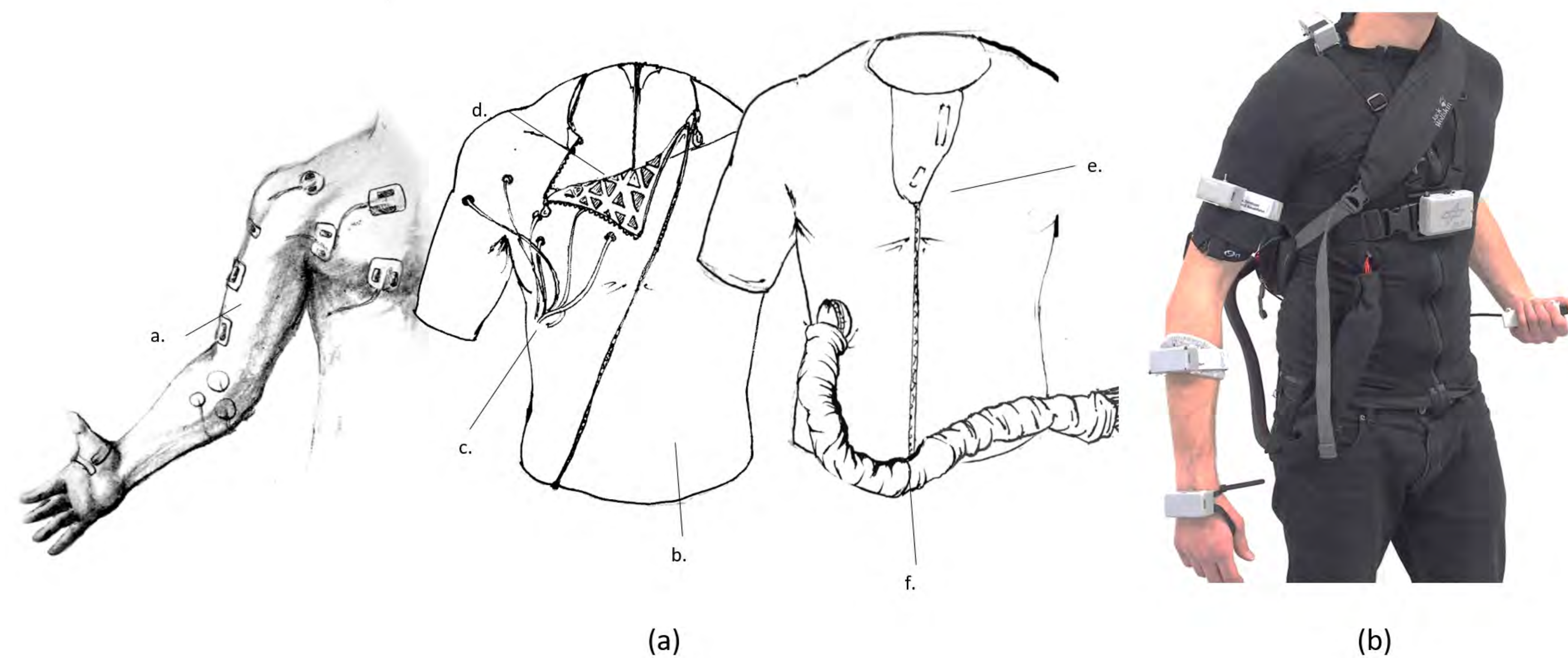


Figure 1: **a:** MyoCeption system elements. In the picture, from left to right, one can see the surface electrodes applied to the user's skin, which are fitted with Velcro hooks on the outside (a). The inner compression jacket (b) features holes (c) to run the electrode cables through, and is fitted with Velcro loops on the inside, so as to ease electrode application (d). The outer jacket (e) groups the cables in a single umbilical (f) connected to the control electronics, and provides further compression. **b:** Picture of the full setup as worn by a user.

METHODS

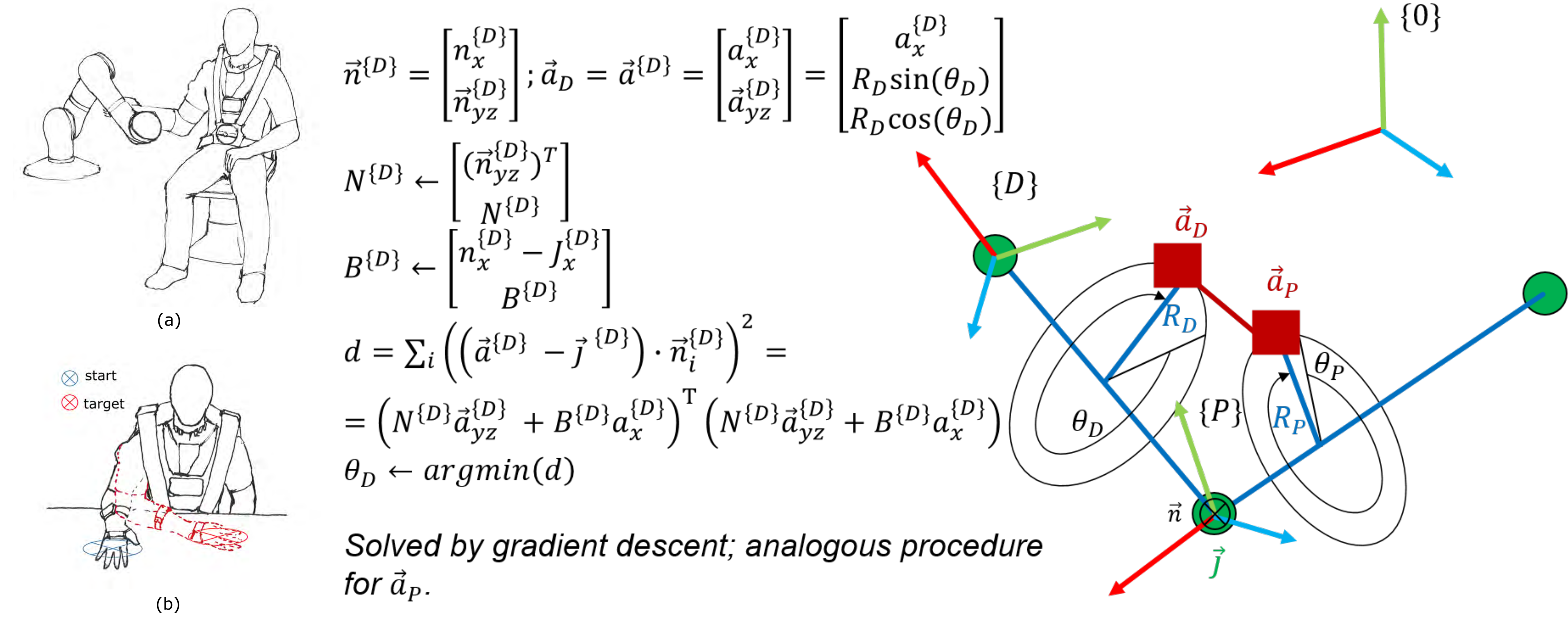


Figure 2: **Left:** Experimental setups to characterize the system. **a:** the user's torso is immobilized and their forearm is coupled to a force/torque sensing machine (such as a robotic arm fitted with torque sensors at the joints or a multidimensional load cell). **b:** The user sits at a table or a surface which sustains most of the arm's weight. The MyoCeption is used to induce movement towards a target hand position on the table starting from a randomized hand position. **Right:** Calibration procedure: the most likely position of the stimulated muscle group's anchor points is computed by analyzing the maximal angular velocity vector of the twitch resulting from a sharp stimulation current.

RESULTS AND FUTURE WORK

The system can be used to exert forces on the user and many possible control structures can be tested. A comparison of calibrated vs not calibrated system showed a significantly smoother movement when using the calibrated system ($t(12) = 2.2720, p < 0.05$) during the tabletop experiment (see Fig. 2 left b). The metric used was the spectral arc length (SPARC) index (calibrated: $-5.4942(2.6726)$, not calibrated: $-13.7934(9.9898)$). Several questions remain open:

- Determination of the optimal muscle recruitment strategy is still open. At the moment, the control system simply selects the nearest neighbour among the muscle groups on a certain joint in terms of elicited torque compared to the needed torque.
- While impedance control seems to be promising, other control architectures would be conceivable and could potentially be a better fit for certain tasks.
- For the case of impedance control, determination of task-specific stiffness, dampening and integration matrices is a non-trivial problem.
- For usage in rehabilitation, an adequate intent prediction solution has yet to be found.
- Naturally, tests in a clinical setting have to be performed to assess the potential value of the system as an element in a task-oriented rehabilitation program.

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TOPIC: Rehabilitation and assistive robotics

P-109

Table Docking System and Negative Obstacle Detection for a Smart Wheelchair

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Smart wheelchairs are expected to have a significant impact on the quality of life of people with severe mobility restrictions. By utilizing a shared control approach involving cooperation between a human user and a machine, a new generation of wheelchairs, can enhance the user's autonomy while providing the necessary assistance, limiting wheelchair-related accidents. Past research has shown that most of these accidents were attributed to tips and falls due to changes in surface elevation. Until now most smart wheelchair related studies have focused on detection of obstacles, while few have considered so-called negative 'obstacles' [1] or developed methods for user assistance in traversing ramps. Informed by clinical need [2], a shared control framework for smart wheelchairs is being developed within the ADAPT project [3]. The current work aims at contributing to the project by detecting negative obstacles including descending ramps and second at improving user participation and independence by enabling the user to park at a table or desk more comfortably. The system has been integrated in the wheelchair software through Robot Operating System (ROS). It uses an IMU to give information on surface inclination at the wheelchair's current position while Time of Flight (ToF) sensors have been included to detect changes in surface elevation to identify if there is a ramp, a drop-off or descending stairs ahead of the wheelchair. This information can be used to adjust online the wheelchair's velocity. Additionally, ToF sensors have been also used to detect if there is a table within range and hence depending on the table's height provide respective messages in ROS for the optimum wheelchair positioning. Experimental results confirm the feasibility of our method.

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TOPIC: Rehabilitation and assistive robotics

P-110

Minimally-Supervised Robot-Assisted Therapy After Stroke: A Feasibility Study in a Clinical Setting

Devittori, Giada 1; Dinacci, Daria 2; Romiti, Davide 2; Califfi, Antonella 2; Petrillo, Claudio 2; Rossi, Paolo 2; Ranzani, Raffaele 1; Gassert, Roger 1,3; Lambercy, Olivier 1,3

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3: Future Health Technologies, Singapore-ETH Centre, Campus for Research Excellence And Technological Enterprise (CREATE), Singapore

Minimally-supervised robot-assisted therapy, i.e. patients training on their own with robotic devices without the constant supervision of a therapist, might be a promising solution to support neurorehabilitation after stroke, as it could help increase therapy dose with minimal additional load on the already limited resources dedicated to rehabilitation [1].

To allow effective therapy while reducing therapist supervision to the minimum, rehabilitation devices have to meet several requirements, such as being able to assess and monitor patients' level of impairment and to customize therapy difficulty to each user. We developed a platform (building on the ReHapticKnob robot [2]) for minimally-supervised therapy of hand sensorimotor function after stroke. To increase its usability and make sure the robot could be used without constant supervision, a set of algorithms to adapt, control and customize therapy to each patient was integrated [3].

To investigate the feasibility of minimally-supervised robot-assisted therapy in a clinical setting and its effect on therapy dose, we are testing the platform with 13 subacute stroke inpatients. Subjects are first taught how to perform the therapy exercises with the device (supervised therapy), and then progressively move to a minimally-supervised therapy setting, where they can independently access the robot and train with it during their free time as well as dedicated sessions.

Preliminary results ($n = 6$) confirmed that this therapy approach is feasible. During the minimally-supervised phase, compliance to the protocol was good ($>75\%$) and therapy dose could be increased ($+46\%$ physical therapy time on average).

This supports the idea that minimally-supervised robot-assisted therapy might allow to increase therapy dose for stroke survivors without adding burden on therapists, and opens the door to the use of this technology not only for in- and outpatient rehabilitation in a clinical setting, but also for home rehabilitation.

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This work was supported by:

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TOPIC: Rehabilitation and assistive robotics

P-111

Shopping Assistance for People Who Are Blind or Have Low Vision

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According to the World Health Organization in 2019, approximately 2.2 billion people are blind or have visual impairments. People who are blind or have low vision (B/LV) rely on assistance from others as well as from assistive technology to complete many everyday tasks, which require visual sensory information.

We initially conducted a survey of devices for people who are B/LV which focused on the sensor packages used that enable indoor and outdoor sensing, the information communicated to the user through different feedback methods, and the tasks these devices are designed to assist people with. After discovering a need for object finding devices in our survey, we distributed a questionnaire to local agencies for people who are B/LV. Our first questionnaire focused on learning about assistive devices that are commonly used by this population, as well as challenges that they face while shopping. From this questionnaire, we found that there is a need for a device to assist with various tasks while shopping, including navigating to desired products, reading information on labels, and helping with tasks while purchasing items. In a follow up questionnaire, we asked questions to gather feedback on our initial design plans for this device including how beneficial they thought it would be, how the device should communicate information to them, and any privacy concerns they had with sharing data to build a map shared between users.

Our proposed design uses a smartphone and its built in sensors to provide shopping assistance. Simultaneous Localization and Mapping (SLAM) will be used to map the stores and provide navigation instructions to users. These maps will be community updated, where all devices will contribute data to ensure that the maps are kept up to date. Additionally, this device will communicate information to the users primarily through speech.

This work was supported by:

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TOPIC: Robotics for clinical practice

P-112

Combined use of LOKOMAT and RYSEN for gait training in spinal cord injury

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Regaining the ability to walk is one of the main goals of spinal cord injury (SCI) rehabilitation. Any kind of locomotor training should be based on four main principles: 1) Maximisation of weight bearing on the legs, 2) Optimisation of sensory cues, 3) Optimisation of kinematics and 4) Maximisation of recovery, minimising compensation. Many patients require some degree of assistance and adaptation to perform this kind of training, and technology can provide them with the necessary support. We present a way to integrate two technological systems: LOKOMAT pro V6 and RYSEN. The use of robot-assisted gait training in neurorehabilitation has become widespread since it enables an increased dose of task-specific gait training. LOKOMAT allows mass walking practice and the optimization of its features is related to challenging the strength of the lower extremities through the reduction of the body weight support and the guiding force. Similarly, the use of the upper limbs during exercises with immersive virtual reality facilitates a dual-task environment with automated gait. Along with other strength and cardiovascular exercises with the upper limbs, this kind of training can increase muscle activation of the legs. RYSEN is a multidirectional weight support system that applies forces to the subject through a harness and allows him to move freely over the work surface. RYSEN guarantees safe training, allowing the patient to perform challenging tasks with the necessary body weight support and facilitates variability of movement patterns, increased demands for balance and interaction with different elements of the environment. Depending on the patient's mobility, the tasks are directed towards different goals, such as standing, walking or other task-specific training. Our experience shows that providing different perceptual inputs and motor demands through the integration of assistive devices and adequate graduation of support may be key factors to enhance gait recovery.

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Combined use of LOKOMAT® pro V6 and RYSEN® for gait rehabilitation in spinal cord injury

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INTRODUCTION

Many patients require some degree of **assistance** and **adaptation** to perform gait training.

LOKOMAT is the reference for robotic gait training. It enables **massed practice** of gait training (1). Recent evidence has shown that **cardiovascular intensity**, **muscular effort** and **variability** are relevant variables in gait training (2).

RYSEN is a multidirectional weight support system that applies forces to the patient through a harness and allows him to **move freely** over the work surface (3). Depending on the patient's mobility level, the tasks are directed towards different goals, like standing, gait training, or task-specific training.

OUR EXPERIENCE

Incomplete SCI T11 AIS C

LOKOMAT + VIRTUAL REALITY



- Immersive virtual reality facilitates a dual-task environment with automated gait
- Walkthrough experience, feedforward of movement
- Oculus Q1® games

LOKOMAT+ AEROBIC TRAINING



- Battle rope, boxing, reaction time training
- Sets of 30 seconds to the maximum, with 30 seconds of rest
- Heart rate monitoring

RYSEN + FUNCTIONAL MOBILITY



- Challenging tasks with the necessary body weight support
- Variability of movement patterns
- Increased demands for balance and interaction with the environment

PROGRESSION

↑Speed ↓Body Weight Support
↓Guidance Assistance ↓Support of upper limbs

CONCLUSION

Our experience shows that providing different perceptual inputs and motor demands through the integration of assistive devices and adequate graduation of support may be key factors to enhance gait recovery.

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TOPIC: Rehabilitation and assistive robotics

P-113

Design and Development of a Spherical Five-Bar Thumb Exoskeleton Mechanism for Post-Stroke Rehabilitation

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Rehabilitation of hand function is crucial for the recovery of normal life quality after stroke. Here we describe the kinematic design and development of a two degree-of-freedom (2 DOF) spherical 5-bar thumb exoskeleton to augment the FINGER [1] rehabilitation robot, which assists the index and middle fingers individually in naturalistic curling motions. FINGER was successful in quantifying finger strength, proprioception, and the degree of motor impairment [2]. Combined with FINGER, the thumb exoskeleton module enables natural grasping motions to both the index and middle fingers, allowing broader hand therapy and assessment following stroke.

The path of the middle phalanx of the thumb was recorded from six healthy subjects during: a) thumb-to-index, and b) thumb-to-middle finger grasping motions. Fitting spheres to the digitized trajectory data of each subject allowed normalization of the data from all subjects to a common center and radius. A 2-revolute-joint serial-chain mechanism was synthesized to achieve two normalized grasping trajectories. The resulting trajectories were sampled as targets for mechanism synthesis of a 2-DOF spherical 5-bar mechanism. The optimization of the spherical 5-bar included constraints for symmetry and cost-function penalties for poor manipulability. The parallel nature of the spherical 5-bar places the actuators at the base of the module, allowing for desirable characteristics including high backdrivability, high controllable bandwidth, and low inertia. A functional prototype was developed from the resulting kinematic design, including replaceable thumb-cuffs to accommodate different hand sizes. Fit and function of the device is tested on multiple healthy subjects. A low-level controller with gravity, friction and force compensation was implemented to reduce the resistance of the robot to subject-initiated motion. Future work includes developing multiple therapy and assessment paradigms to be implemented with the device.

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TOPIC: Rehabilitation and assistive robotics

P-114

A Novel Passivity based Friction Gravity Adaptive Admittance Control for Upper Limb Human Exoskeleton Interaction

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Exoskeletons for assessment require transparent (i.e., low impedance) human-robot interaction, which are often achieved via admittance control. However, vibration instability limits force/torque (FT) responsiveness. In this work, a 5-DOF upper limb robot (BLUE SABINO) is used to evaluate the influence of modelling (dynamics) and compensation (gravity, friction) errors toward diminished control efficacy.

A novel adaptive admittance controller is proposed which improves performance by learning accurate gravity forces and scaling friction compensation without inducing chatter. The control is like [1], with addition of adaptive friction compensation. Adaption adjusts a gravity model based on CAD mass and forward kinematic estimates and scales a friction model which are initialized using a fit to a friction-velocity map established using the procedure given in [2].

Control is heuristically tuned, using guidelines suggested in [3]. Inner loop PD gains are tuned on sinusoidal trajectories to achieve tracking over a target frequency range of 0.1-5Hz. Adaption rates are set to optimize convergence when the inner loop is excited by (3-5) uniform random sampled target frequencies. The outer loop admittance filter sets a trajectory target based on FT sensor input. The filter is designed to attain stable, low impedance interaction using minimal energy storage/dissipation. Outer loop performance is gauged on human/robot power exchange.

Experiments show proposed adaptive admittance control reduced power exchange over the initial admittance controller. Comparison of 1st and 2nd order admittance filters indicated that the former is more responsive and more prone to vibration. Vibration observed when the user increased arm stiffness suggests that reduced system energy dissipation is a driver of vibration instability. Simulation supports this hypothesis and demonstrates that the proposed adaptive controller compensates more effectively for high stiffness levels in the human arm.

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TOPIC: Computational neurorehabilitation

P-115

A Locomotor Cat Model for Restoring Walking after Complete Spinal Cord Injury: Assessing the Capability of a Predictive Control Algorithm

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Intraspinal microstimulation (ISMS) is a micro-implant for restoring walking after spinal cord injury (SCI) that can be placed in small regions of the spinal cord to activate the locomotor networks and produce functional movements. Since implanted electrodes in this system can activate different synergistic muscle groups, their activation needs to be coordinated using a control strategy. To date, various rule-based ISMS control strategies have been tested in animals, resulting in in-place stepping in cats with complete SCI [1], and also long distances of functional over ground walking in anesthetized cats, without injury [2]. Recently, a predictive control strategy was also tested, for the first time, in anesthetized cats with simulated incomplete SCI, where feedback signals of the “intact” limb moved by the experimenter were used to predict the state of walking for the paralyzed limb, controlled by ISMS [3]. The goal of this project is to expand the predictive algorithm to produce walking after a complete SCI model, where both hindlimbs are paralyzed.

To verify the feasibility of the algorithm, a musculoskeletal model of cat hindlimbs was developed in MATLAB. Walking was divided into 4 phases and muscle synergies in each phase were activated with constant motoneuron excitation, leading to a muscle activation pattern that mimics ISMS. A control strategy was designed to transition between phases, using feedforward flexor-extensor oscillations and also feedback from limb angles and ground reaction forces. Reinforcement learning in combination with Pavlovian control, inspired by classical conditioning, are being implemented to learn the feedback signals ‘ pattern and produce a predictive walking strategy.

This is a critical step towards producing personalized bipedal walking. If successful in simulation, testing will be performed in animals with complete chronic SCI, where it is expected to generate stable feedback signals, leading to more accurate control decisions.

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TOPIC: Robotics for clinical practice

P-116

The Longitudinal Evolution of Proprioceptive, Motor, and Sensorimotor Hand Impairments in the Sub-Acute Phase After Stroke

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It is unclear whether proprioceptive, motor, and sensorimotor function of the hand follow similar recovery patterns in the sub-acute phase after stroke. Gaining a better understanding of their co-evolution is crucial to predict recovery more accurately and adapt therapies accordingly. However, there is currently a lack of sensitive assessment methods to comprehensively quantify recovery patterns.

In this ongoing study, subacute stroke inpatients were assessed biweekly using a novel robotic device, the ETH MIKE, a one-degree-of-freedom end-effector robot targeting the index finger metacarpophalangeal joint [1]. The device can provide well-controlled stimuli to the finger and measure subjects' kinematic and kinetic response, and contains a battery of sensitive and reliable robot-assisted assessments with, among others, position matching (proprioception), active range of motion (motor) and trajectory following (sensorimotor) tasks [2].

So far, 41 participants were recruited. In the preliminary results, we observed a large variability in the recovery patterns across patients, which is likely linked to lesion size and location. Proprioceptive and motor recovery were to some extent dissociated, as we found more subjects that improved in motor function than in proprioception. Furthermore, subjects that had worse proprioception at baseline exhibited worse performance in a robotic sensorimotor task at discharge, which highlights the importance of proprioception in sensorimotor recovery. The first results also indicated validity of robot-assisted assessments, as robotic metrics correlated moderately to strongly with clinical and neurophysiological measures (somatosensory/motor evoked potentials) at inclusion. The insights gathered in this study promise to increase our understanding of sensorimotor recovery after stroke and, in the future, could impact the way therapy plans are designed and personalized.

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The Evolution of Proprioceptive and Motor Hand Impairments after Stroke

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Introduction

Motor and/or somatosensory (proprioceptive) function is frequently affected after **stroke** [1,2]. It is unclear whether these hand impairments follow similar **recovery patterns** in the sub-acute phase after stroke. Gaining a better understanding of their co-evolution is crucial to predict recovery more accurately and adapt therapies accordingly. However, there is currently a **lack of sensitive assessment methods** to comprehensively quantify recovery patterns [3]. To provide a fine-grained and objective evaluation of hand impairments and their change over time, we are using a validated set **robot-assisted assessments** [4,5].

Robot-assisted assessments

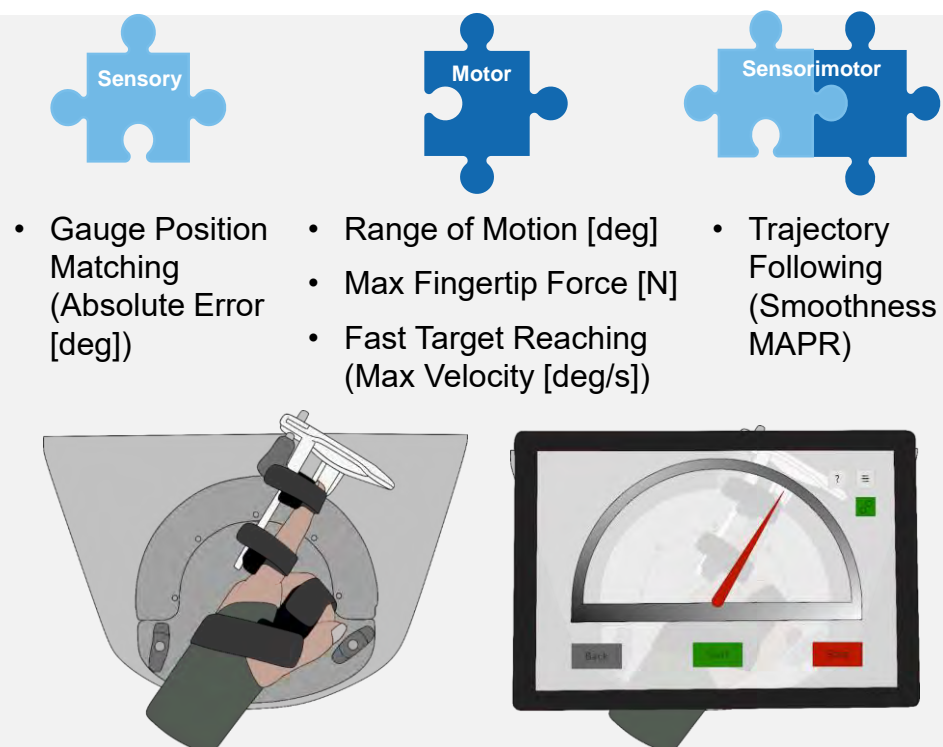


Figure 2: All robotic tasks have a graphical user interface on a tablet computer located above the index finger interface that ensure interactivity of the assessments. For example, in the Gauge Position Matching task, the robot moves subject's finger to a specific position, and he/she needs to indicate on the tablet screen the perceived finger position. The GUI also displays results and allows to choose tasks from menu.

Clinical study protocol and apparatus

- Robotic assessments were performed with **sub-acute** stroke subjects every two weeks between inclusion and discharge from the rehabilitation clinic.
- Clinical assessments, e.g., kinesthetic Up-Down Test (kUDT) and Fugl-Meyer Motor Assessment, as well as neurophysiological assessments (i.e., Somatosensory and Motor Evoked Potentials SSEP/MEP) were performed at inclusion and after 4 weeks. Additionally, MRI scans were collected.
- Inclusion criteria: < 3 months post-stroke & ability to understand instructions.

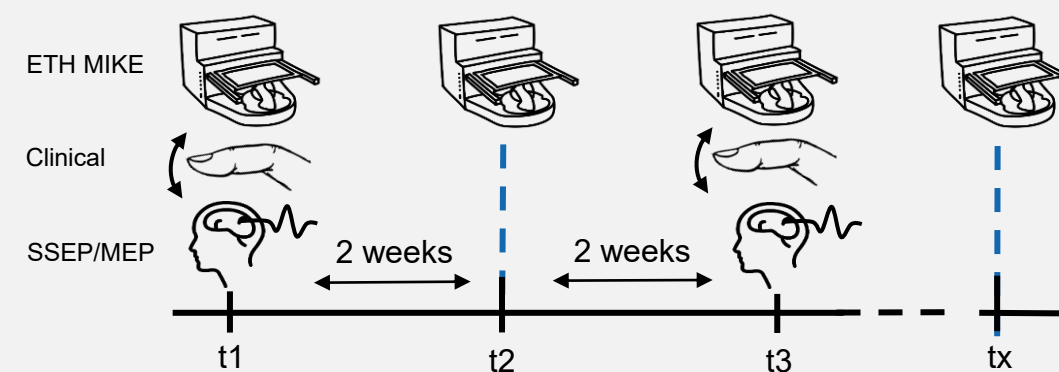


Figure 1: Robot-assisted assessments were performed on a one-degree of freedom robotic end-effector platform (ETH MIKE) [4,5], which exclusively targets index finger metacarpophalangeal joint of each hands individually. The robot can passively move the index finger to a desired position and precisely measure its activity (displacement, velocity, force). During experiments subjects were seated in an upright position, grasping a handle and a tablet computer placed above the hand displaying instructions.

Main findings and future work

- Robotic metrics **are capable of** measuring variability in impairments and their recovery profiles over the course of conventional rehabilitation in the sub-acute phase after stroke. The trend of increasing performance over time is captured by both robotic and clinical assessments.
- Assessment of patient-specific impairment profiles could guide **therapy planning and adaptation** and therefore enhance recovery.
- Next steps** consist of further investigation of the **coevolution of sensory and motor impairments** over the course of recovery.

Results and discussion

So far data of **30 subjects** were analyzed in this ongoing study (13 females, age 68 ± 9). At inclusion subjects were 35 ± 16 days post-stroke. There was a large variability in impairment levels and recovery patterns between subjects (Figure 3). There was a **significant improvement** per-subject level in **proprioception** between T1 and T2 (paired t-test p-val.: 0.031), as well as T1 and T3 (p-val.: 0.026). According to finger active range of motion as an example robotic measure, **motor function improved significantly** between T1 and T3 (paired t-test p-val.: 0.037). We aim at recruiting 50 subjects overall.

Table 1: Mean and standard deviation of proprioceptive and motor impairments, captured longitudinally by robotic and clinical scores.

Matching Error [deg]	kinesthetic Up-Down	Finger AROM [deg]	Fugl-Meyer Motor
T1: 15.41 ± 5.12	T1: 1.83 ± 1.34	T1: 49.45 ± 25.12	T1: 31.00 ± 24.83
T2: 13.90 ± 5.44	T2: 2.07 ± 1.20	T2: 51.59 ± 26.31	T2: 37.24 ± 23.73
T3: 13.34 ± 6.36	t-test p-val.: 0.032	T3: 55.78 ± 24.33	t-test p-val.: <0.01

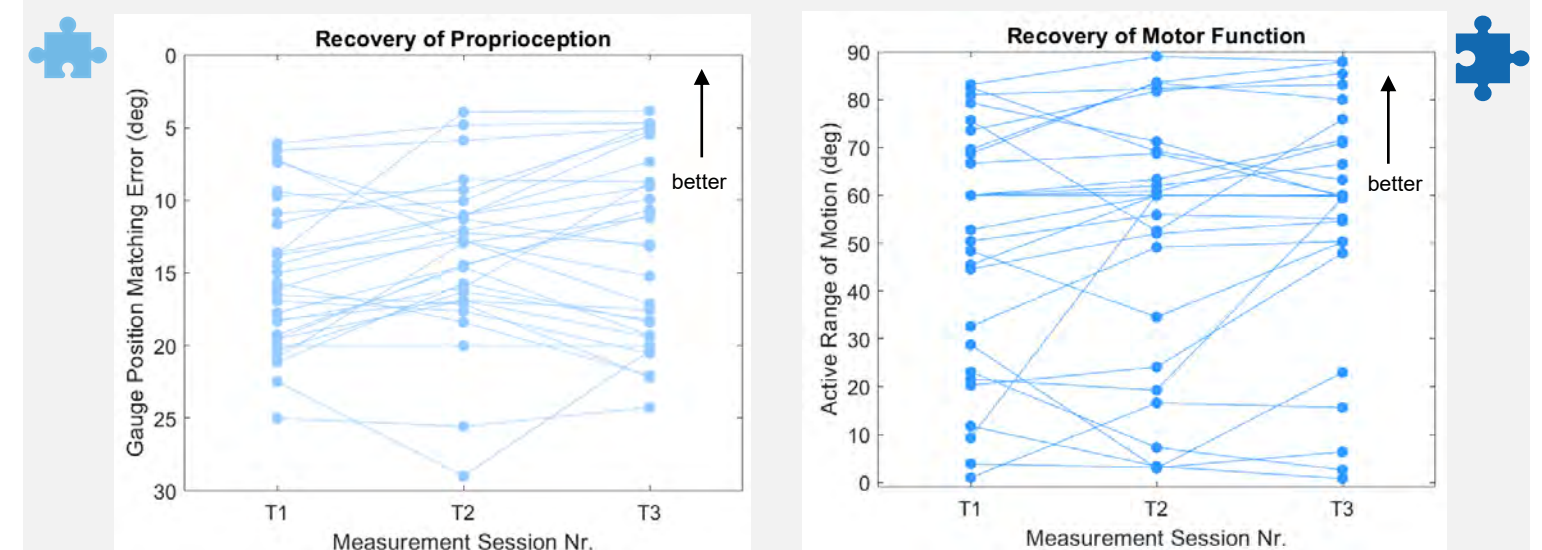
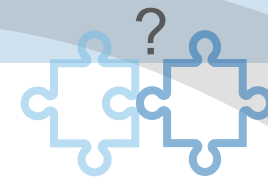


Figure 3: Variability in impairment levels and recovery profiles between subjects for two example robotic metrics – Gauge Position Matching Error and Active Range of Motion at the level of the index finger MCP joint. Three points joined by a line represent a recovery curve for a single subject. There is an overall trend of increasing performance over time, which is expected given the sub-acute phase.

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TOPIC: Rehabilitation and assistive robotics

P-117

Tailoring a Robotic Hand Orthosis For Individuals With Tetraplegia in View of Independent Use at Home

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Robotic hand orthoses (RHO) can provide grasp assistance and have the potential to increase the independence and quality of life of people with tetraplegia [1]. Many RHO have proven their benefit for selected users in controlled environments. However, for daily use in home settings, wearable robots often lack in usability, translating into low technology acceptance. One factor limiting the usability is the fact that each user represents a unique context of use. A “one-size-fits-all” design is often not expedient, stressing the need for individually tailored solutions [2].

Building on a promising RHO prototype (RELab tenoexo [3]), we aim to meet this demand by fully tailoring the design and functions of the orthosis to individual users with tetraplegia. Through usability studies, we reviewed the key components of the RHO, and developed tailoring options for each of them, providing an extensive catalogue of solutions for adjusting to the individual needs of a user. Besides size and aesthetics, we can adapt the RHO ‘s degrees of freedom and how these are actuated and controlled. We offer various intention detection strategies such as buttons, voice control, an app, or IMU-based solutions, which can be combined or used separately. To ease donning and doffing, several physical attachment solutions based on gloves, straps, magnets, or snaps are provided. On the software side, we can - among other options - adapt the opening and closing speed, grasp force, and triggering modes.

By providing such fully tailored devices, in combination with extensive user training, we aim to enable safe, confident, and efficient use by target users. We hypothesize that this will increase their willingness to incorporate the device into their daily lives and help transition to unsupervised, independent use at home. This lays the groundwork for an ongoing study to investigate long-term benefits and user acceptance of the tailored RHO as well as the co-evolution between users and their devices.

References: Chu, CY, and Patterson, RM. “Soft robotic devices for hand rehabilitation and assistance: A narrative review.” *Journal of NeuroEngineering and Rehabilitation* (2018); 15(1): 1-14.
DOI:10.1186/s12984-018-0350-6., Kintsch, A., and DePaula, R. “A framework for the adoption of assistive technology.” *SWAAAC 2002: Supporting learning through assistive technology* (2020), 1-10., Butzer, T, et al. “Fully wearable actuated soft exoskeleton for grasping assistance in everyday activities.” *Soft Robotics* (2020).

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This work was supported by: Swiss National Science Foundation SNSF through the National Centre of Competence in Research on Robotics

Tailoring a Robotic Hand Orthosis For Individuals With Tetraplegia in View of Independent Use at Home

Jessica Gantenbein¹, Jan T. Meyer¹, Jan Dittli¹, Roger Gassert^{1,2}, and Olivier Lambercy^{1,2}

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² Future Health Technologies, Singapore-ETH Centre, Campus for Research Excellence And Technological Enterprise (CREATE), Singapore

Motivation

- Robotic hand orthoses (RHO) providing grasp assistance have the potential to increase quality of life of people with tetraplegia [1].
- Many RHO have proven their benefit in controlled environments, but lack in usability in daily settings, translating into low technology acceptance.
- One major usability hurdle is the fact that each user represents a unique context of use, stressing the need for individually tailored solutions [2].

The RELab tenoexo



- RHO designed for assistance in various activities of daily living [3]
- Soft compliant finger mechanism
- Four grasp types (2 active and 1 passive DOF)
- Lightweight and low profile

Tailoring options

Required tailoring options were defined based on user feedback collected in a usability study involving 15 participants with SCI [4].



1 Control system

Intention detection: buttons, voice-, EMG-, force sensors-, or IMU-based control

Smartphone application: y/n, private/dedicated phone, settings & design

2 Actuation system

Actuation modes: grasp types, movement speed, trigger delay

Remote actuation system: detachable y/n, cable length

Back module: placement, attachment, color, battery type, charging system

3 Hand module

Wrist design: size, flexible design vs passive orthosis with fixed angle

Finger design: size, ratio of extension/flexion force, thumb opposition mechanism

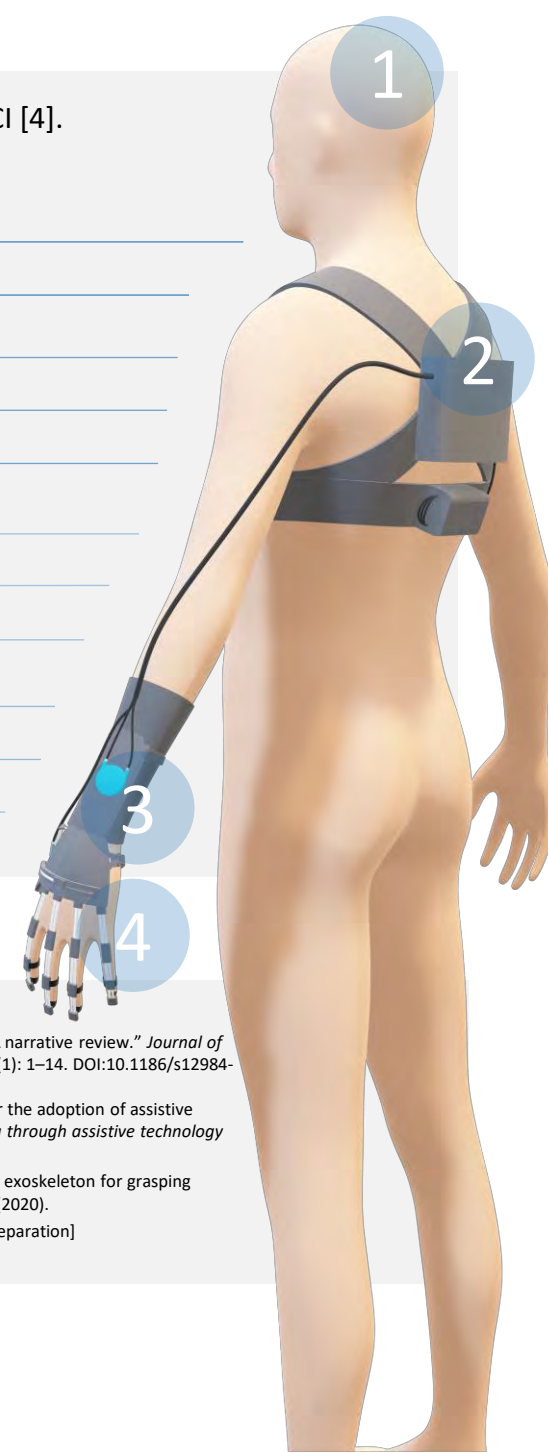
Aesthetics: colors, add-ons, skins (covered exoskeleton fingers)

4 Attachment system

Wrist attachment: straps & wrist sleeve, full-hand or cut-open glove

Finger attachment: Velcro, straps, magnets, snaps

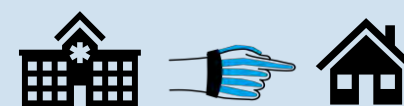
Donning strategy: independent vs. with help from caregiver



Hypothesis & Outlook

Technology acceptance can be increased by achieving **safe, confident and efficient** use of a RHO through a **fully tailored device and extensive user training**.

This may promote the transition from the controlled laboratory or clinical setting to **unsupervised, independent use in daily life at home**.



References

- [1] Chu, CY, and Patterson, RM. "Soft robotic devices for hand rehabilitation and assistance: A narrative review." *Journal of NeuroEngineering and Rehabilitation* (2018); 15(1): 1–14. DOI:10.1186/s12984-018-0350-6.
- [2] Kintsch, A., and DePaula, R. "A framework for the adoption of assistive technology." *SWAAC 2002: Supporting learning through assistive technology* (2020), 1–10.
- [3] Bützer, T, et al. "Fully wearable actuated soft exoskeleton for grasping assistance in everyday activities." *Soft Robotics* (2020).
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TOPIC: Robotics for clinical practice

P-118

Functional Real-world Robotic Assisted Training: The EMU Feasibility Study

Crocher, Vincent 1; Fong, Justin 1; Klaic, Marlena 2; Davies, Katie 3; Sutton, Emma 4; Tan, Ying 1; Oetomo, Denny 1; Galea, Mary P 5; Brock, Kim 4

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Robotic assisted interventions for upper-limb neurorehabilitation have been shown to be in general as effective as traditional therapy [1] but their benefit appear to fail to translate fully to functional outcomes [2]. Robotic training is often restricted to on-screen gaming without functional, real-world, interactions, whereas this is often part of classic rehabilitation programs.

We introduce here the preliminary results of a study investigating the feasibility and potential benefits of functional, real-world, robotic-assisted training. The study used the EMU, a 3D manipulandum robot, in which the hand of the assisted arm can be free.

As part of a larger study [3], we observed the use of the EMU by therapists at a major hospital rehabilitation centre. The device was used to provide physical assistance, prescribed by the therapists, while patients were practicing rehabilitation movements without screen interaction and with or without real-objects, over a table-top.

To date five patients with neurological injury undertook 23 rehabilitation sessions of 50mins on average with 114+/-66 repetitions per session. Interactions used were De-weighting, Assistive and Passive mobilisation. No adverse events were reported.

All therapists involved (N=5) were successfully able to use the device after a one-hour training. In interviews, therapists reported clear benefits in using the device for functional training: "You can do more hands on"; "It allows [me] to step back and watch while doing movements"; "It certainly allows [the patient] to do more repetitions".

From these preliminary results, robotic assisted training of functional tasks is feasible in a semi-supervised setting but will require some additional engineering developments to reduce the therapists supervision need. This type of training appears beneficial from the therapists point-of-view but additional studies are required to show its potential interest on clinical outcomes.

References: Mehrholz, Jan, et al. "Systematic review with network meta-analysis of randomized controlled trials of robotic-assisted arm training for improving activities of daily living and upper limb function after stroke." *Journal of neuroengineering and rehabilitation* 17.1 (2020): 1-14., Rodgers, Helen,

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Functional Real-World Robotic Assisted Training

The EMU Feasibility Study



Vincent Crocher, Justin Fong, Marlena Klaic, Katie Davies, Emma Sutton,
Ying Tan, Denny Oetomo, Mary P Galea, Kim Brock



Background

Robotic assisted interventions for upper-limb neurorehabilitation have been shown to be in general as effective as traditional therapy [1] but their benefit appear to fail to translate fully to functional outcomes [2]. Robotic training is often restricted to on-screen gaming without functional, real-world, interactions, whereas this is often part of classic rehabilitation programs.

As part of a larger multi-site study, we explored the use of the EMU rehabilitation robot for real-world functional training, where the use of the device was selected and driven by the clinicians.

The EMU



- 3D manipulandum
- Large workspace
- On-screen and off-screen training
- Sitting or standing practice

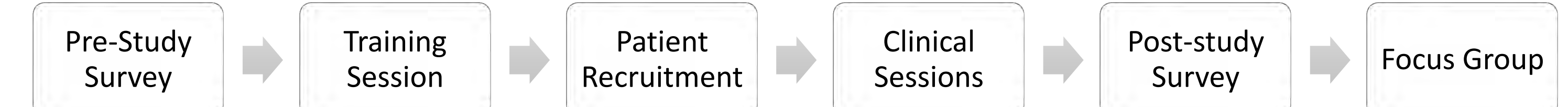


Protocol

- 3 sites: 1 private clinic, 2 major hospitals
- Any patient w/ neurologically impaired UL
- 6 sessions/patient (1h each)
- Iterative improvements of device functionalities

Objectives

- Feasibility of using a 3D manipulandum
- Determine use by clinicians and integration in practice
- Measure Acceptance, Barriers and Facilitators in adoption of these devices (TAM)



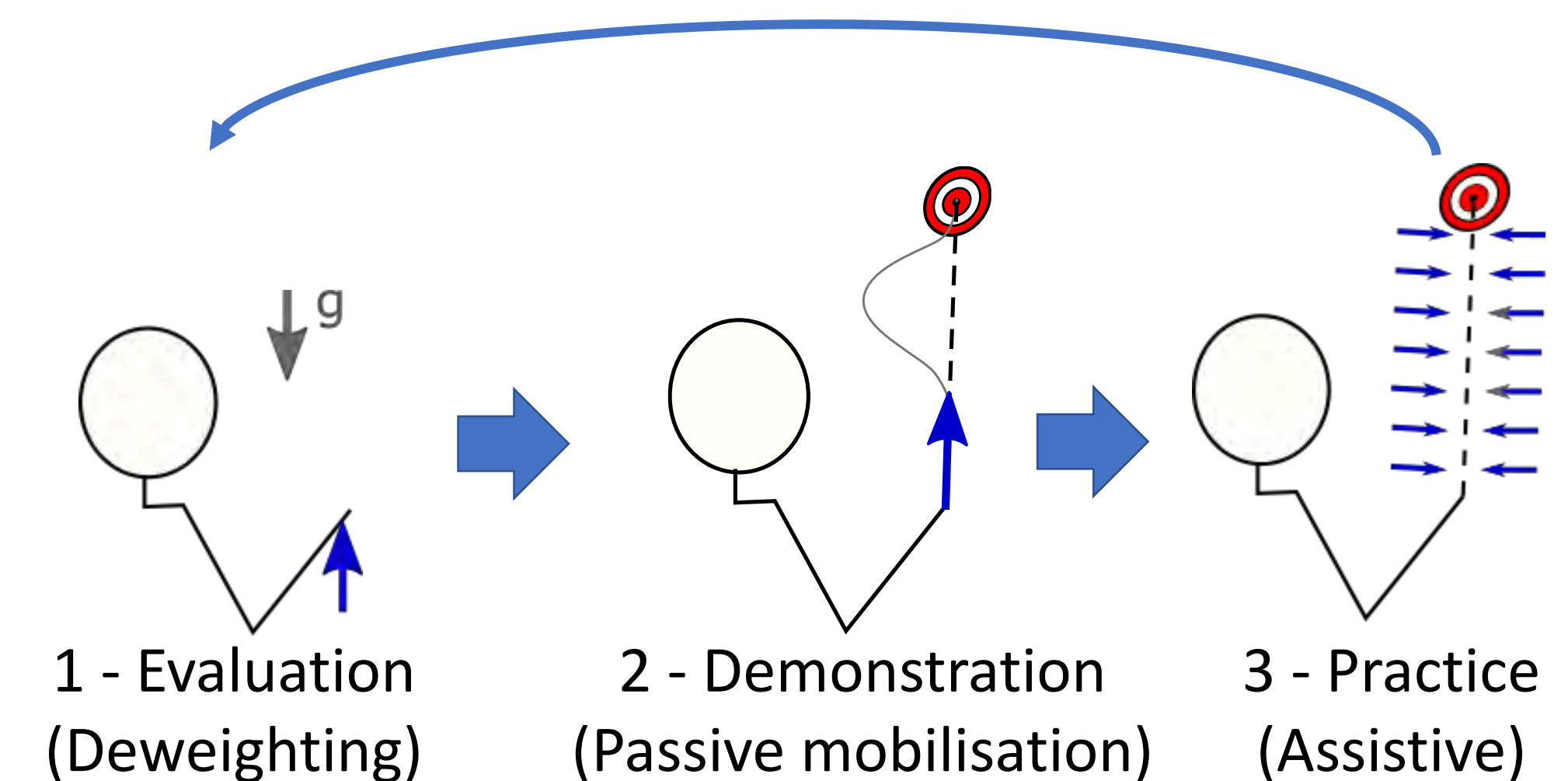
At the first two sites of this study, the EMU was primarily used with on-screen gaming [3].

At the third site (St Vincent's Hospital) the focus was placed on Real-World training

Sessions process

Task breakdown in movements of interest for each patient and practiced over the session.

Process empirically defined and refined by therapists during the first sessions of the study:



Preliminary results

- ✓ No adverse events reported (23 sessions)
- ✓ Independent use by all therapists (N=5) after one session
- ✓ 114±66 repetitions/session (53 mins)
- ✓ Positive patients' engagement (despite no gaming)

"You can do more hands on"

"It certainly allows [the patient] to do more repetitions"

"It allows [me] to step back and watch while doing movements"

- A path to clinical evaluation
- Robotic improvement required to reduce supervision need
- Another promising use of robotic to improve functional outcomes?

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TOPIC: Rehabilitation and assistive robotics

P-119

Validation of a gait safety metric for robot-assisted walking with an alcohol intoxication experiment

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2: Spinal Cord Injury Center, Balgrist University Hospital, Medical Faculty, University of Zurich, Zurich, Switzerland.

Falls have been identified as a major public health problem and their incidence increases when considering people suffering from neuromuscular gait disorders. Numerous studies have identified gait variability as a quantitative feature of walking that predicts risk of falls [1]. In this context, soft wearable robots for rehabilitation and daily assistance have the potential to estimate gait stability relying on data collected from their integrated sensors, in addition to their primary goal of providing support. This study assessed the validity of gait safety metrics extracted from the sensors embedded in a wearable robot. Data collected from five IMUs integrated in the Myosuit were used to implement a state-of-the-art gait variability index (GVI) [2] consisting of the weighted sum of 9 spatiotemporal gait parameters. We tested the intra-subject validity of the GVI in different walking conditions known to increase the risk of falling, i.e. progressively higher levels of blood alcohol concentration (BAC), with one healthy participant. Inter-subject validity was assessed by comparing GVI scores in a cohort of healthy individuals and participants with lower limb motor impairments. Progressively higher levels of BAC resulted in a consistently higher GVI score compared to the sober condition. In agreement with the assumption that the risk of falling is higher for an impaired person than healthy control [3], results showed a significantly lower GVI score for the latter population. The study demonstrates the possibility to evaluate risk of falling during robot-assisted walking. The proposed index could be a valuable metric to (1) assess gait safety in future studies that investigate the walking pattern of exoskeleton users, (2) evaluate changes in gait stability over time to inform physical therapy interventions, (3) include measures of gait safety in the cost function of a human-in-the-loop optimization algorithm to tune the assistance parameters of a wearable robot.

References: J. M. Hausdorff, "Gait variability: methods , modeling and meaning Example of Increased Stride Time Variability in Elderly Fallers Quantification of Stride-to-Stride Fluctuations," vol. 9, pp. 1-9, 2005, doi: 10.1186/1743-Received., A. Gouelle, F. Megrot, A. Presedo, I. Husson, A. Yelnik, and G. F. Penneçot, "The Gait Variability Index: A new way to quantify fluctuation magnitude of spatiotemporal parameters during gait," *Gait Posture*, vol. 38, no. 3, pp. 461-465, 2013, doi: 10.1016/j.gaitpost.2013.01.013., R. Mazumder, C. Murchison, D. Bourdette, and M. Cameron, "Falls in people with multiple sclerosis compared with falls in healthy controls," *PLoS One*, vol. 9, no. 9, pp. 1-7, 2014, doi: 10.1371/journal.pone.0107620.

This work was supported by: National Centre of Competence in Research Robotics (NCCR Robotics)

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TOPIC: Prediction of rehabilitation outcomes using machine learning

P-120

Machine learning-based prediction of upper limb rehabilitation outcomes in multiple sclerosis: a preliminary analysis

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2: Rehabilitation Center Valens, Valens, Switzerland;

3: Future Health Technologies, Singapore-ETH Centre, Campus for Research Excellence And Technological Enterprise (CREATE), Singapore.

Multiple Sclerosis often leads to upper limb impairments, which can be targeted with neurorehabilitation interventions. However, upper limb rehabilitation outcomes of persons with multiple sclerosis (pwMS) remain highly variable [1]. Hence, there is a growing need for quantitative models predicting therapy outcomes for pwMS and accordingly personalizing therapy content and intensity. The goal of this study is to define and validate a data-driven model predicting therapy outcomes using 18 features including demographics and clinical assessments, collected on 89 pwMS at the admission of a 3-week inpatient rehabilitation program. In addition, a technology-based assessment of upper limb impairments, the Virtual Peg Insertion test (VPIT), provides 10 additional digital health metrics on movement pattern and grip force control [2]. Based on a random forest regressor, we could accurately predict Box and Block Test (BBT) outcomes with a cross-validated root mean squared error of 6.3 ± 4.0 blocks/min, which is well below the minimal detectable change of the clinical scale. The most important predictor is the BBT score at admission. Additionally, significant predictors include VPIT metrics. This provides the basis for an individualization of therapy protocols in the context of limited clinical resources and highlights the benefit of sensitive digital metrics which promise to advance predictive models.

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This work was supported by: The National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme.

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TOPIC: Rehabilitation and assistive robotics

P-121

Comparative Evaluation of Hip Partial Assistance Control Strategies

Manzoori, Ali Reza 1; Ijspeert, Auke 1; Bouri, Mohamed 1
1: EPFL, Lausanne, Switzerland

For partially assisting people who are already able to walk, hip exoskeletons can be a viable solution, in view of the trade-off between the ideal performance outcome and the practical limitations of implementation. They can be designed to be lightweight, and do not require adding distal mass to the user. Moreover, hip muscles may be less energetically efficient than the ankle muscles [1], which suggests that decreasing the muscle power at the hip can increase the energy efficiency of gait. However, such a decrease requires effective assistance, which concerns the open question of “how to apply the right assistance torque at the right time?”. Building on previous work [2], in this study we introduce 2 controllers for hip exoskeletons for level-ground walking. The first controller (C1) works based on estimating gait cycle progression from the hip movements, and applies assistance torque accordingly. The other controller (C2) determines the assistance torque from the ratio of the ground reaction forces on the feet. These strategies are experimentally assessed and compared to a baseline controller (C0) applying an assistance torque as a function of percent gait cycle, calculated from the time since heel-strike.

The implementation is carried out on an exoskeleton developed by our research group in collaboration with the company Sonceboz. The experiments are conducted with healthy adults walking on a treadmill at different speeds while wearing the device. The performance of each controller is evaluated individually and comparatively with respect to C0, by analyzing hip kinematics and checking the synchronicity of the assistance torques with user's gait. The heart rate of the subjects and their subjective preferences between the controllers are also used to compare the physical exertion and the perceived quality of assistance. The heart rate and subjective preference scores show a better performance for C2, even though speed/torque analysis seems to be in favor of C1.

References: Sawicki, Gregory S., Cara L. Lewis, and Daniel P. Ferris. 2009. “It Pays to Have a Spring in Your Step.” *Exercise and Sport Sciences Reviews* 37(3):130. doi: 10.1097/JES.0b013e31819c2df6., Baud, R., A. Ortlieb, J. Olivier, M. Bouri, and H. Bleuler. 2018. “HiBSO Hip Exoskeleton: Toward a Wearable and Autonomous Design.” Pp. 185-95 in *New Trends in Medical and Service Robots, Mechanisms and Machine Science*, edited by M. Husty and M. Hofbaur. Cham: Springer International Publishing.,

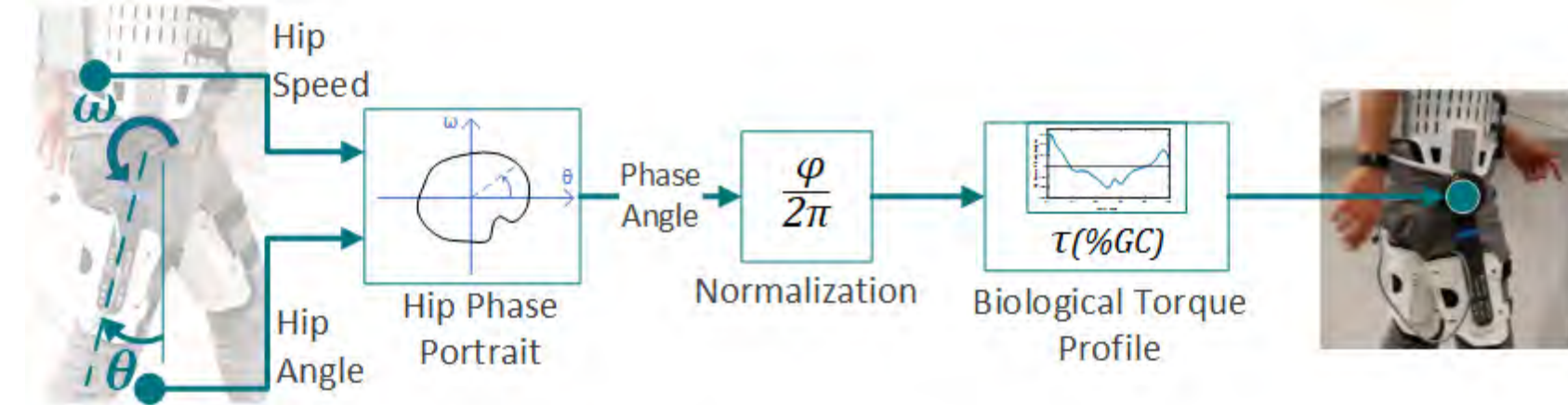
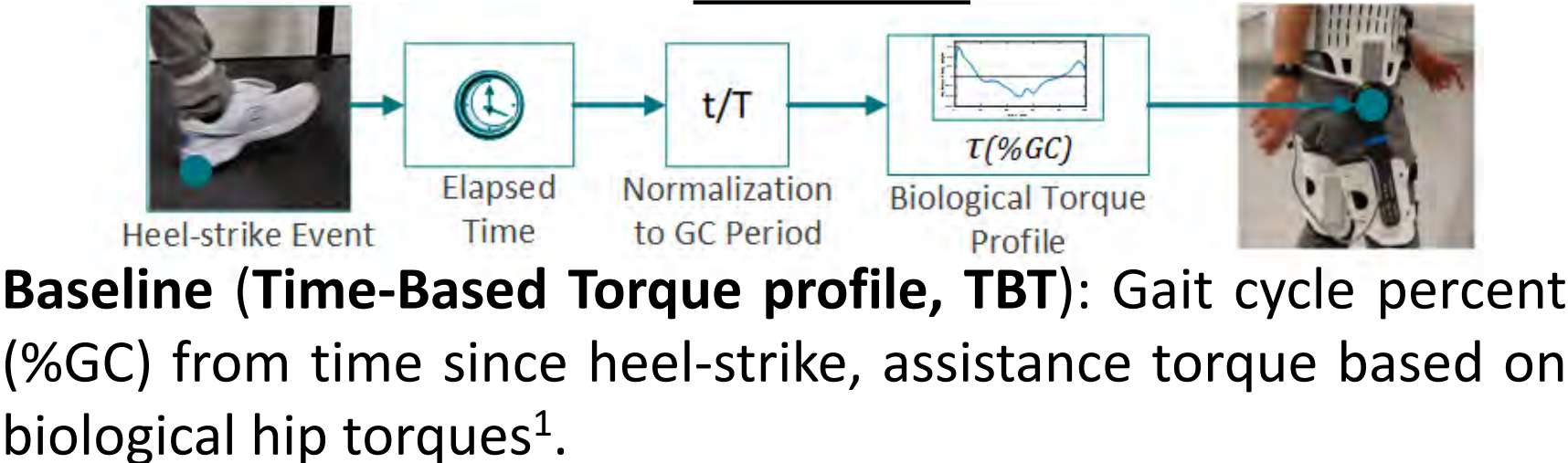
This work was supported by: EU (Horizon 2020 Marie Skłodowska-Curie grant agreement No. 754354), Sonceboz SA

INTRODUCTION

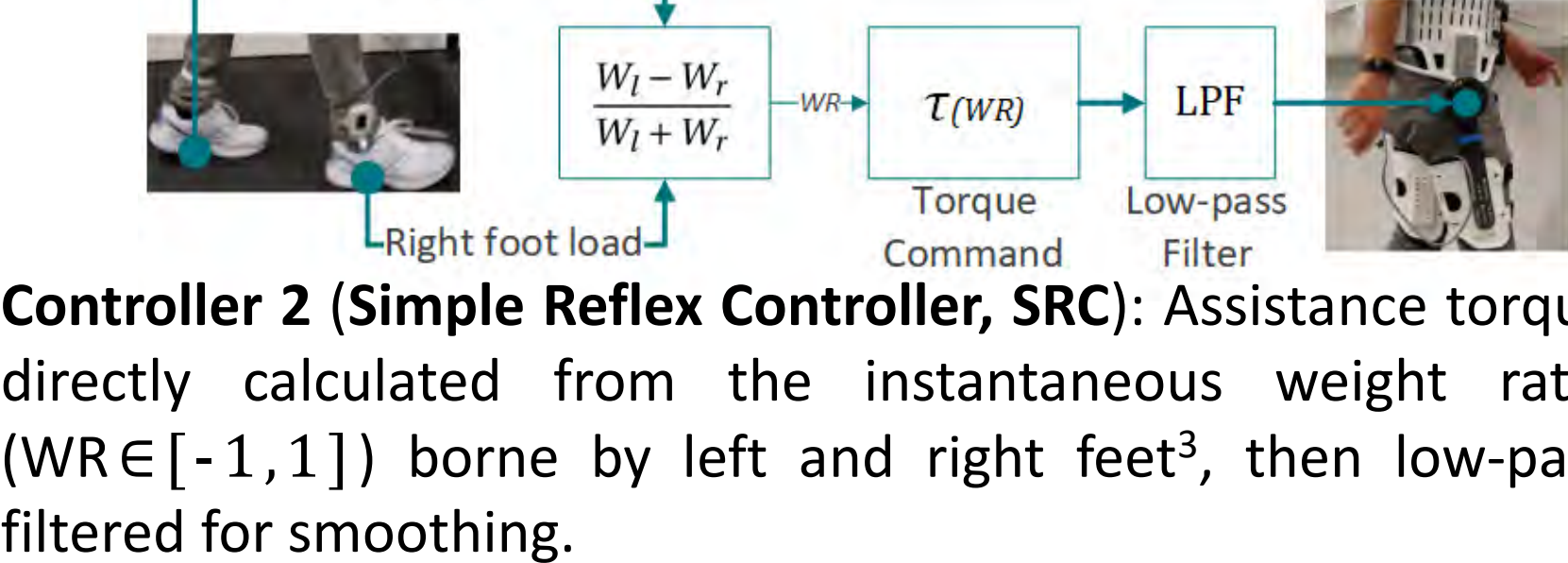
Control of hip exoskeletons to effectively assist the gait of persons without serious impairments (e.g. able-bodied or the elderly) is a challenging problem since the exoskeleton must fully adapt to user’s walking. Here, we report a **preliminary comparative investigation of 2 different control methods and a baseline controller using a bilateral hip exoskeleton with healthy subjects**. The baseline controller uses time-based synchronization and a pre-defined torque profile. The 1st controller relies on explicit but time-independent synchronization and the same torque profile as the baseline, while the 2nd controller uses implicit synchronization and a directly calculated torque based on foot loads. The studied outcomes are the **synchronization of the assistance with users’ movements, the assistance power, and the subjective preferences of the users**.

MATERIALS & METHODS

Controllers

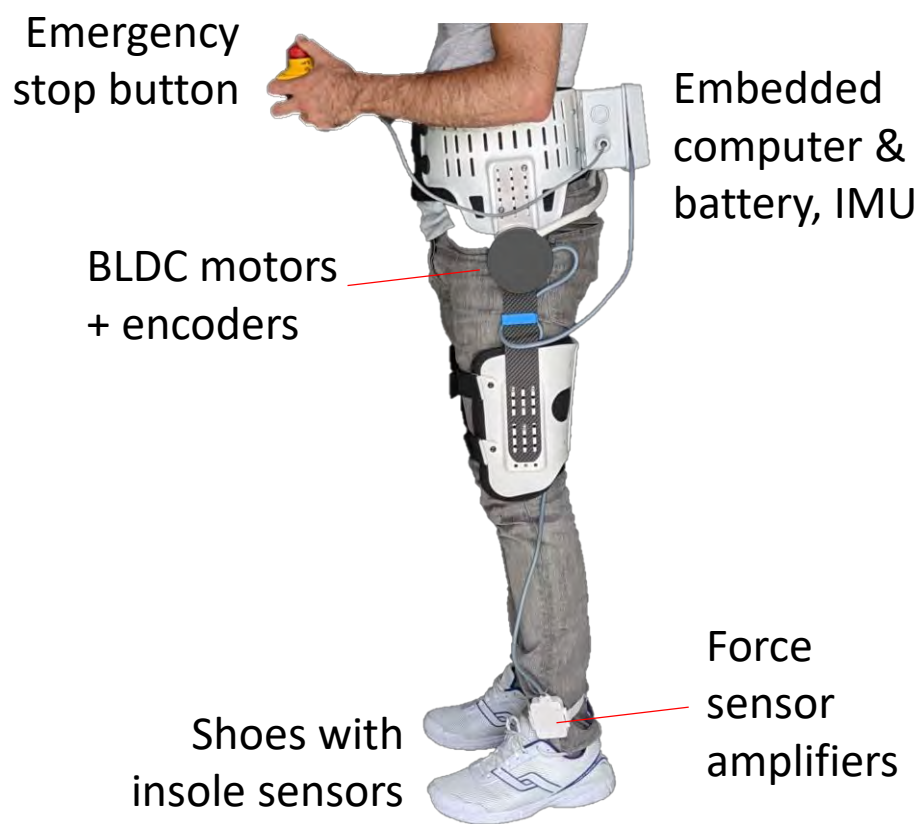


Controller 1 (Hip Phase-based Torque profile, HPT): %GC from the polar angle of hip phase portrait², torque profile same as TBT.



Device: e-Walk

- 13 N.m continuous and 35 N.m peak torque per joint.
- Embedded computer running the control loop at 500 Hz.

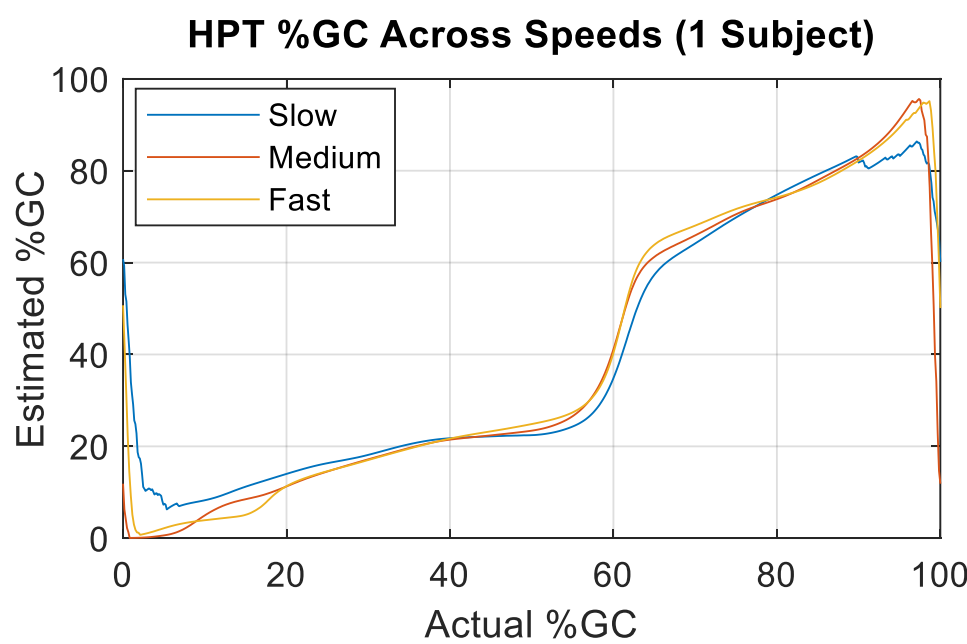
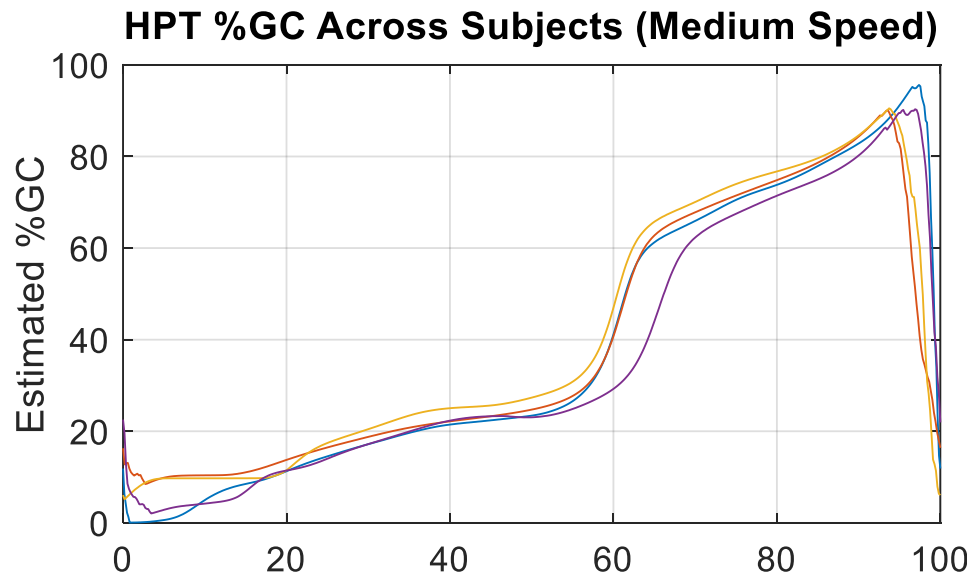


Experimental Protocol

- **Treadmill walking at 3 speeds:** slow (0.7 m/s), medium (1.1 m/s) and fast (1.5 m/s), 3 minutes each (9 min. total)
- **4 healthy subjects** (3 male, 1 female, 34±9 years)

HPT %GC Estimation Reliability

- Distortion in stance and early swing
- Very consistent across speeds, fairly consistent across subjects



Averaged Subjective Preference Scores

“How easy is it to walk with this controller compared to unassisted walking?”

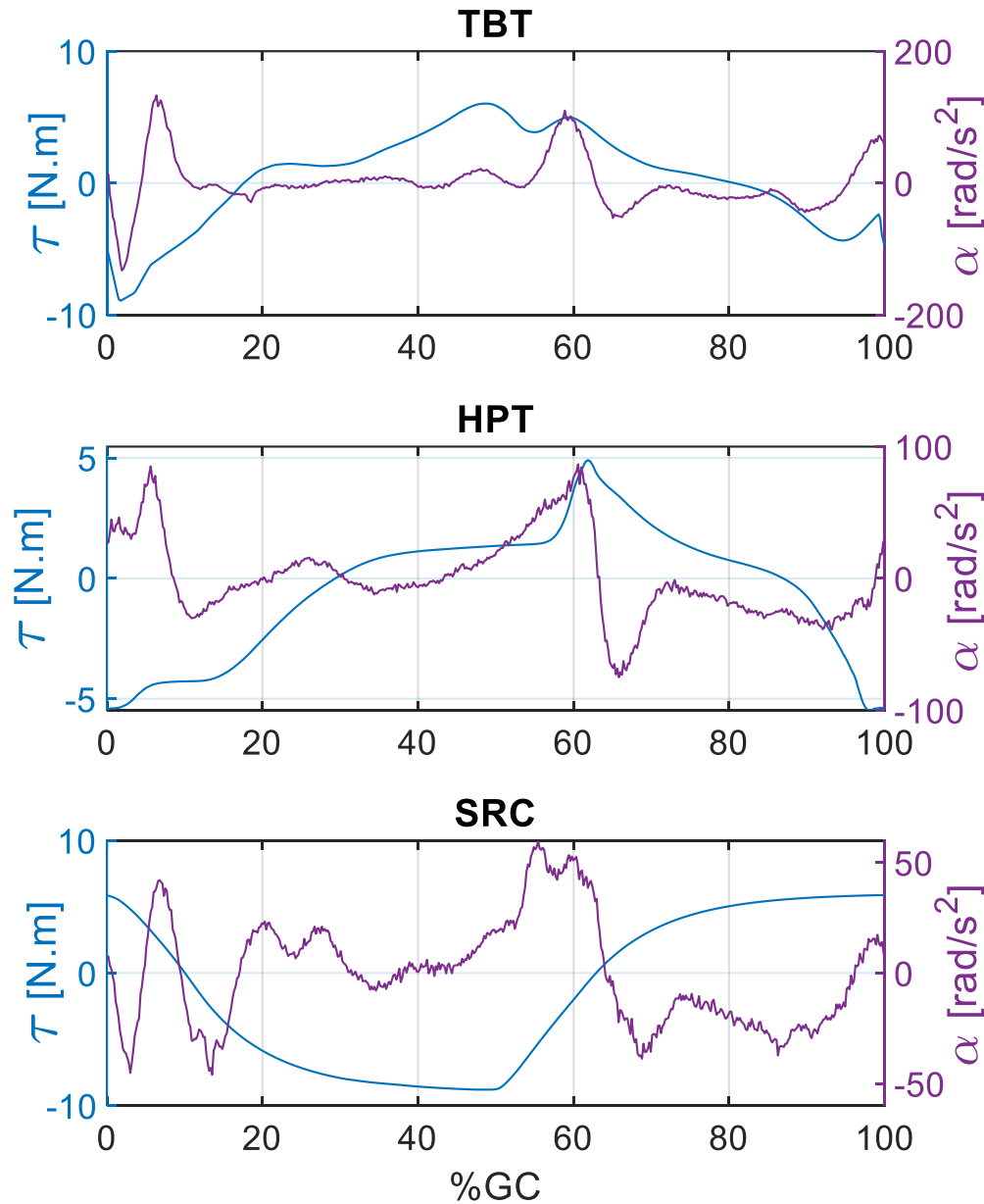
Controller	TBT	HPT	SRC
Score (out of 5)*	3 ± 1.1	3 ± 0.8	4.5 ± 0.6

*1: very hard, 2: hard, 3: no difference, 4: easy, 5: very easy

RESULTS

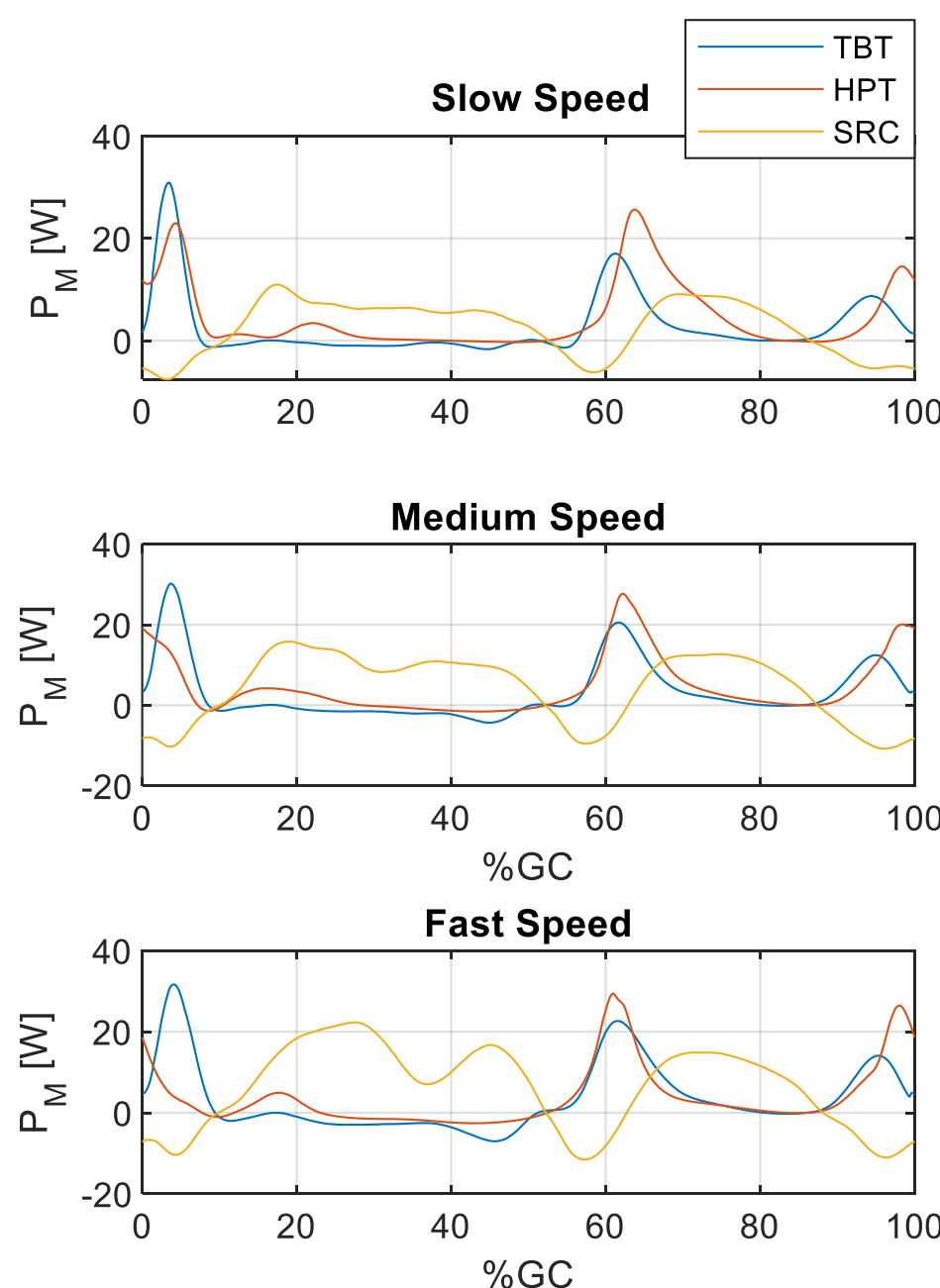
Assistance Torques and Accelerations

- TBT: Torque peaks lead hip angular acceleration peaks. Peak assistance in early stance and pre-swing.
- HPT: Torque peaks concurrent with acceleration. Peak of assistance in early stance and swing.
- SRC: Torque peaks out of phase with acceleration. Peak of assistance in late stance and swing.



Assistance Power

- TBT and HPT: Bursts of positive power in early stance and early swing, almost no negative power.
- SRC: Visible peaks of negative power in early stance and early swing, followed by steady periods of positive power in mid-stance and mid-swing.



CONCLUSIONS

- Direct %GC estimation from hip phase angle is not very accurate due to nonuniform progression rate. It can be improved with processing, and may require subject-specific tuning.
- HPT and TBT are better synchronized with the movement, %GC distortion of HPT does not significantly affect the synchronization.
- Smoothness of the torques seems to play a stronger role than supplying positive power in shaping users’ perception of being assisted.

ACKNOWLEDGEMENTS

This project is supported by the company Sonceboz and has received funding from the European Union’s Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 754354.

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TOPIC: Rehabilitation and assistive robotics

P-122

Robust Sensor Fault Detection for a Shared Control Wheelchair

Eberle, Henry 1; Carlson, Tom 1

1: University College London

Safety is a key consideration for any assistive technology, but it is a much more complex factor when considering shared control, where an algorithm enhances the user's ability to operate a device (in our case, a powered wheelchair) by blending its control input with the user's [1]. This means that a sensor fault could lead the algorithm to make hazardous mistakes that the user, lacking full control, cannot override. Furthermore, this assistance may be helping the user reach the minimum skill threshold for safe wheelchair driving [2], meaning that their permission to use the wheelchair is ultimately dependent on its sensors being accurate. Since no sensor is immune to failure, a shared control wheelchair must be able to detect sensor faults as they occur.

As sensor artefacts are very diverse, it is crucial not to perform error-detection based on prescriptive assumptions. In this study an error-detection system is being developed inspired by the temporal slowness principle: that features in the external environment tend to vary slowly relative to variations in the sensor [3]. For a range sensor of the type used on our smart wheelchair, this means that large, discontinuous changes should usually only occur at the edges of the sensors' range as features come in and out of view, and these will often be detected by more than one adjacent sensor. Using this combination of temporal and geometric priors, we hypothesise that we can identify which sensor readings are most likely to be artefacts, allowing us to iteratively update the probability that each sensor is functioning correctly using Bayesian inference. This will enable the smart wheelchair to identify sensor faults before they become a hazard, without strong assumptions on their nature.

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This work was supported by: European Union Horizon 2020 research and innovation programme under the grant agreement CROWDBOT No 779942.

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TOPIC: Rehabilitation and assistive robotics

P-123

Towards rehabilitation of pathological synergies with volitional movement using a manipulandum robot

Xu, Yangmengfei 1; Fong, Justin 1; Crocher, Vincent 1; Tan, Ying 1; Oetomo, Denny 1.

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In neurorehabilitative therapy, ensuring appropriate movement quality through recruitment of desired muscle synergies is paramount. Should a patient exhibit pathologically synergetic movement, therapies encourage volitional movements with the correct movement pattern, which strengthens neural pathways of those patterns.

A recent study showed robotic devices can encourage movement pattern change without explicit instruction, with an intervention which applied forces at the joints --- i.e. a 'direct' intervention [1]. This work aimed to experimentally investigate (1) whether movement shaping could be driven 'indirectly' --- i.e. applying force in a difference space to that in which the movement change was expected; and (2) whether the performance of such an intervention would change if introduced in a more progressive manner. This was motivated by the potential for simpler devices (e.g. manipulanda) to be used instead of more complex ones (e.g. exoskeletons) in rehabilitation.

In the experiment, a robotic 3D manipulandum applied a resistive viscous force at the subject's hand (i.e. the task space) as a function of the subject's swivel angle to encourage an increase (adaptation) of the latter (i.e. change in the redundant joint space).

Twenty naive, able-bodied subjects were allocated into 2 groups with two different implementations of the intervention: one with a Constant Goal (CG) and another one with a Progressively changing Goal (PG). Subjects were asked to perform reaching tasks -- first without any force field, then within intervention trials. Significant increases of the swivel angle of 4.9° and 6.3° were observed for the CG and PG groups respectively.

These results confirm the feasibility of movement pattern shaping in the redundant joint space by providing a task space intervention without explicit error feedback, suggesting that simple devices may be used in movement pattern shaping for highly redundant tasks in neurorehabilitation.

References: T. Proietti, E. Guigon, A. Roby-Brami, and N. Jarrassé, "Modifying upper-limb inter-joint coordination in healthy subjects by training with a robotic exoskeleton," J. Neuroeng. Rehabilitation, vol. 14, no. 1, pp. 1-19, 2017., ,

This work was supported by: The Australian Research Council Linkage Project LP180101074

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TOPIC: Rehabilitation and assistive robotics

P-124

Enhancing Social Interaction in Upper Limb Rehabilitation Through Co-located and Online Multiplayer Games

Guney su Ozgur, Arzu 1; Khodr, Hala 1; Akeddar, Mehdi 1; Taburet, Victor 1; Roust, Michael 1; Bruno, Barbara 1; Dillenbourg Pierre 1

1: EPFL, Computer Human Interaction in Learning and Instruction (CHILI) Lab, Switzerland

The social aspects of rehabilitation are very important for patients and must be considered when designing a platform, especially for home-based rehabilitation. We proposed co-located and online versions of the previously proposed tangible Pacman game [1,2,3] for upper limb rehabilitation with haptic-enabled tangible Cellulo robots. Our main objective is to enhance motivation and engagement through social integration and also to form a gamified multiplayer rehabilitation at a distance. Thus, allowing relatives, children, and friends to connect and play with their loved ones while also helping them with their rehabilitation together or from anywhere in the world. This is especially relevant in view of the current social distancing measures which have especially isolated the elderly population, a majority of all rehabilitation patients.

References: Guney su Ozgur, Arzu, Maximilian Jonas Wessel, Wafa Johal, Kshitij Sharma, Ayberk vñzgur, Philippe Vuadens, Francesco Mondada, Friedhelm Christoph Hummel, and Pierre Dillenbourg. "Iterative design of an upper limb rehabilitation game with tangible robots." In Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction, pp. 241-250. 2018., Guney su Ozgur, Arzu, Maximilian J. Wessel, Jennifer K. Olsen, Wafa Johal, Ayberk Ozgur, Friedhelm C. Hummel, and Pierre Dillenbourg. "Gamified motor training with tangible robots in older adults: a feasibility study and comparison with the young." Frontiers in aging neuroscience 12 (2020): 59., Guney su Ozgur, Arzu , Louis P. Faucon, Pablo Maceira-Elvira, Maximilian J. Wessel, Wafa Johal, Ayberk vñzgur, Andeol Cadic-Melchior, Friedhelm C. Hummel, and Pierre Dillenbourg. "Towards an adaptive upper limb rehabilitation game with tangible robots." In

This work was supported by: The Swiss National Science Foundation through the National Centre of Competence in Research Robotics 1

REHAB WEEK 2021

23-25 SEPTEMBER 2021
VIRTUAL EVENT



TOPIC: Rehabilitation and assistive robotics

P-125

Serious game based training using an assistive device at home may provide long term improvement in the upper limb function of patients in the chronic phase of stroke

Rozevink, Samantha 1; van der Sluis, Corry 1; Hijmans, Juha 1

1. University of Groningen, University Medical Center Groningen, Groningen, The Netherlands

Background and aims: The arm/hand function of patients in the chronic phase of stroke is often impaired. Technological improvements make it possible to provide intensive therapy to improve the upper limb function at the patients' home. HoMEcare aRm rehaBilitation (MERLIN) is a combination of an unactuated device to train the upper limb at home and a telerehabilitation platform based on serious games. The aim of the study was to investigate the (long term) effectiveness of MERLIN.

Methods: Patients in the chronic phase of stroke trained for 6 weeks, 3 hours per week at home with MERLIN. Shoulder, elbow and hand movements were trained using a variety of serious games. Telerehabilitation was used to assign games and monitor progress. Measurements were performed 6 weeks prior intervention (T0), at start (T1), end (T2), 6 weeks (T3) and 6 months after the intervention (T4). The primary outcome was the Wolf Motor Function Test (WMFT). Secondary outcomes were Action Research Arm Test (ARAT) and Fugl Meyer Assessment (FMA) and quality of life (EQ-5D).

Results: Eleven patients completed the training program. Results showed significant increase in upper limb function on the FMA score between T0-T2 ($p=.02$), T0-T3 ($p=.001$), T0-T4 ($p=.02$), T1-T2 ($p=.02$) and T1-T3 ($p=.001$). WMFT scores significantly improved between T0-T2 ($p=.03$) and T1-T3 ($p=.048$). No effects on ARAT or EQ-5D were found. A decreasing trend was observed in all arm function tests from post-intervention towards six months follow up.

Conclusion: Stroke survivors in the chronic phase of stroke were able to significantly improve their arm/hand function after intensive training with MERLIN, however arm function seemed to decrease over time after cessation of the training.

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TOPIC: Human-machine interfaces in rehabilitation

P-126

The effect of feedback modality on learning a novel wrist visuomotor transformation

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Vision has traditionally been the main sensory modality adopted for conveying sensory feedback when (re)learning new motor skills through human-machine interfaces [1]. However, a previous study suggested that visual feedback may implicitly bias the process of skill acquisition towards suboptimal strategies from the point view of control efficiency [2]. Here we investigated whether proprioceptive and visual feedback differentially impact the strategy for learning a novel redundant visuomotor mapping.

Right-handed participants with no history of neurological impairment learnt to control the velocity of a unidimensional cursor using their dominant wrist to reach as many targets as possible in a given amount of time.

The mapping between wrist rotation and cursor velocity was designed to implicitly encourage individuals to rotate the wrist around an axis corresponding to a predefined combination of flexion/extension and ulnar/radial deviation. Cursor speed was proportional to the projection between the instantaneous rotation axis and the predefined one.

We considered two training conditions. The first group received visual feedback of both the target and the cursor position. For the second group, visual feedback of the cursor was replaced by a passive rotation of the contralateral wrist along the flexion/extension direction by means of a wrist manipulandum [3].

Control guided by visual feedback resulted in a greater number of targets reached per unit time than control guided by proprioceptive feedback, which required more corrective actions at the target. However, the proprioceptive feedback group was able to maximize the alignment with the preferred rotation axis, yielding a more efficient control than the visual feedback group.

These results suggest that, while visual feedback is efficiently integrated to plan movement in extrinsic coordinates, proprioceptive feedback could more effectively convey information about intrinsic task components, related to the joint space.

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This work was supported by: Marie Skłodowska-Curie, project REBoT, G.A. No 750464; NIDILRR, Grant Number 90REG0005-01

Giulia Aurora Albanese^{1,2}, Jacopo Zenzeri¹ and Dalia De Santis¹

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Background

Vision has traditionally been the main sensory modality adopted for conveying sensory feedback when learning new motor skills through human-machine interfaces. However, the visual feedback may implicitly bias the process of skill acquisition towards suboptimal strategies from the point view of control efficiency.

Do proprioceptive and visual feedback differentially impact the strategy for learning a novel redundant visuomotor mapping?

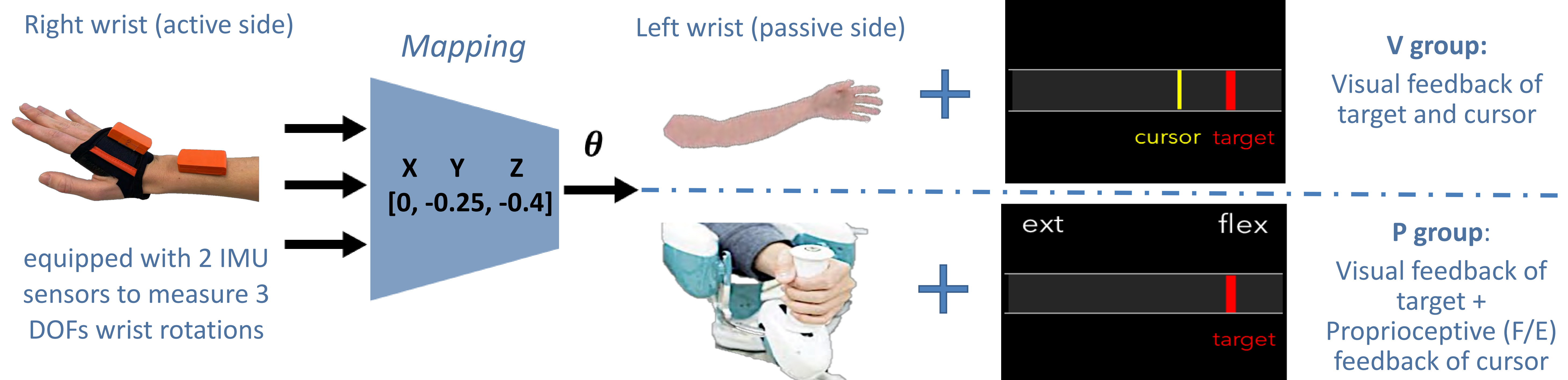
Methods

Training task: to reach as many targets as possible on a line in 6 sessions (B1-B6) of 5 minutes each.

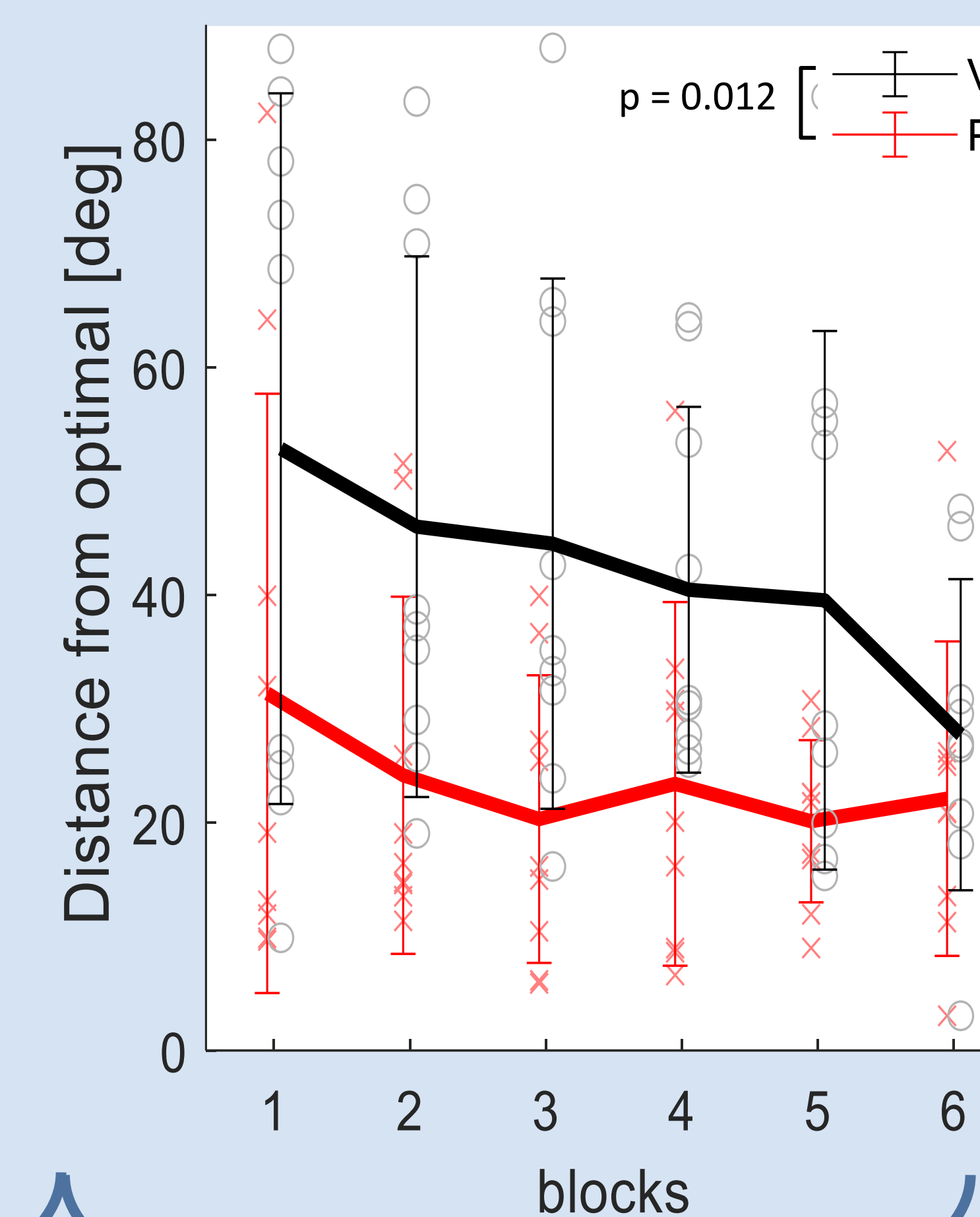
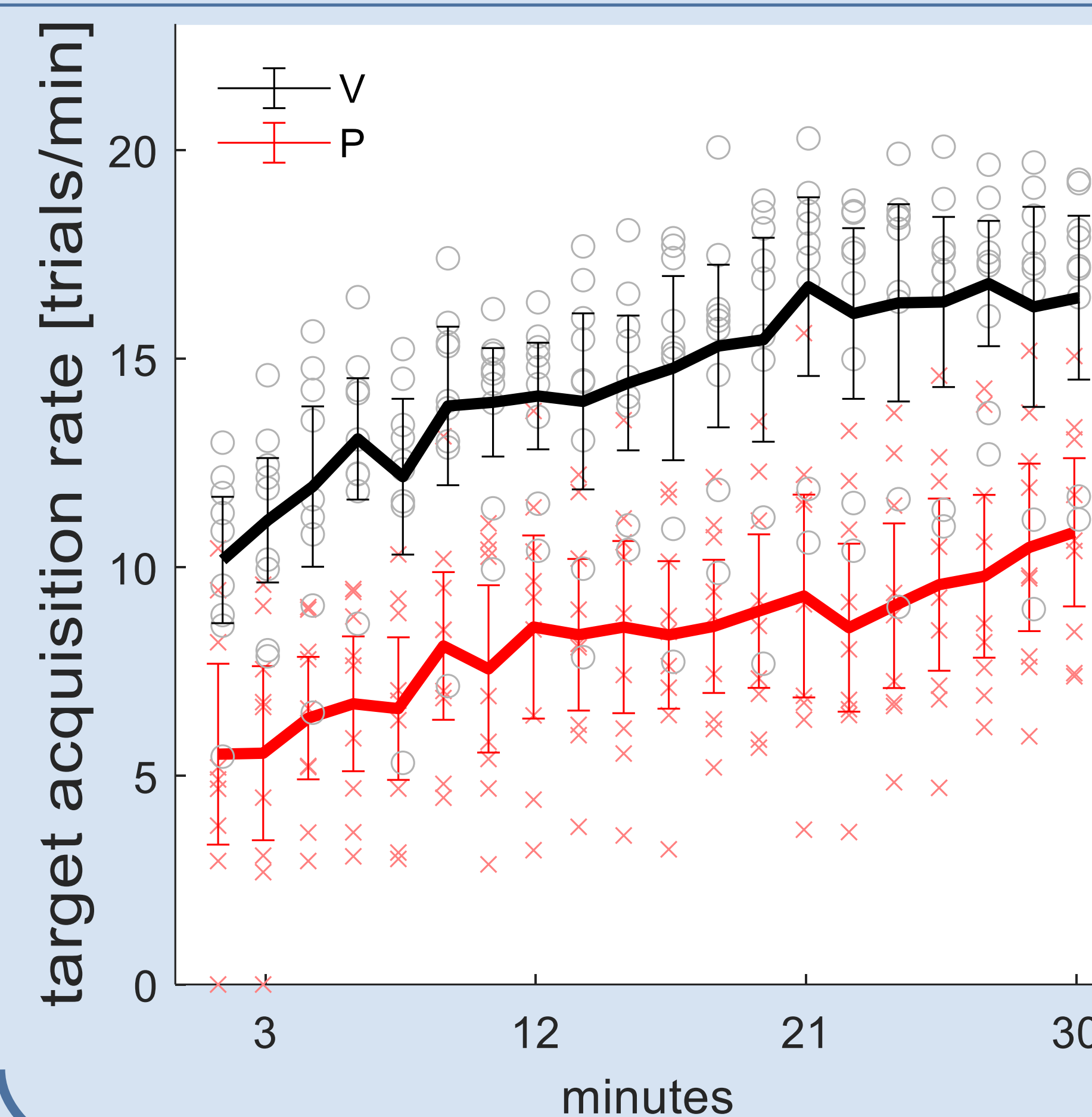
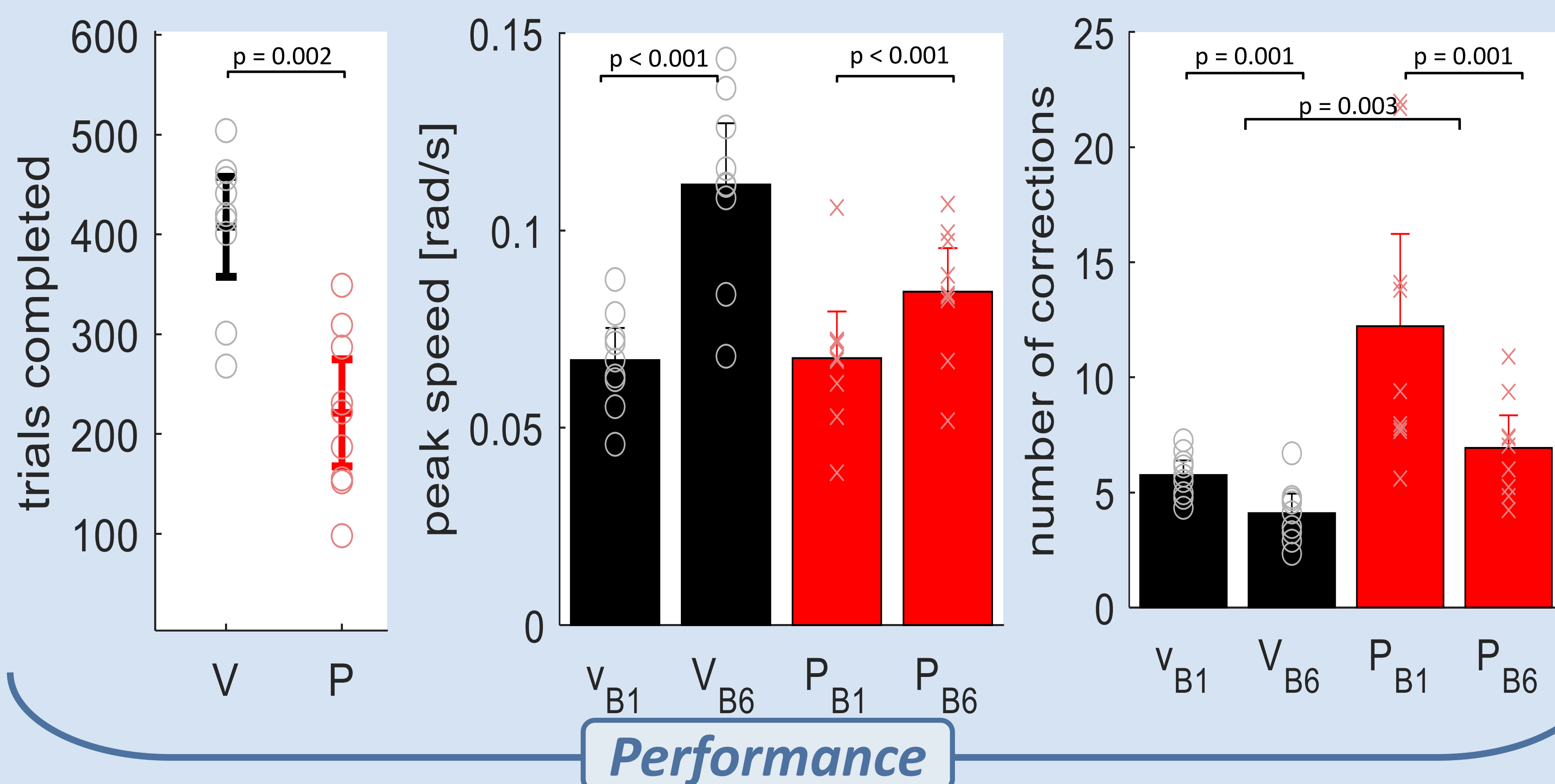
Cursor control by wrist movements: the right wrist instantaneous rotation axis was linearly mapped into the 1D velocity of a cursor on the screen (θ).

Participants: 18 unimpaired subjects (11M, 7F) equally divided in two feedback groups:

- *V group* = visual feedback
- *P group* = proprioceptive feedback



Results



Performance improved for both, but visual feedback yields better control:

- *V* control is more smooth
- *V* reach more targets

The groups learn similarly:

- the change in target acquisition rate is comparable

Proprioceptive feedback yields greater efficiency:

- *P* minimizes the distance from the optimal axis.

Conclusions

Visual feedback is efficiently integrated when planning movements for learning a task defined in extrinsic coordinates, such as a physical location in the space. However, proprioceptive feedback seem to be more effective in conveying information about intrinsic task components, i.e. related to the joint space and to its actual configuration.

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TOPIC: Rehabilitation and assistive robotics

P-127

Multi-Domain Dynamic Modelling of an Upper Limb Rehabilitation Robot for Tracking Patient Progress

Metcalf, Adam 1,2; Levesley, Martin 2; Gallagher, Justin 3; Jackson, Andrew 4

1: University of Leeds, Leeds, UK; 2: University of Leeds, Leeds, UK; 3: University of Leeds, Leeds, UK; 4: University of Leeds, Leeds, UK

Tracking patient progress through a course of robotic tele-rehabilitation requires constant position data logging and comparison alongside periodic testing with no powered assistance. The test data must be compared with previous test attempts and an ideal baseline, for which a good understanding of the dynamics of the robot is required when powered and unpowered. The traditional dynamic modelling techniques for serial chain robotics, which involve forming and solving equations of motion, do not adequately describe the multi-domain phenomena which affect the movement of the rehabilitation robot.

In this study connected dynamic models for a 2-DoF upper limb rehabilitation robot and a 7-DoF mechanical proxy for a human arm are described. The models are built using a combination of SimScape and SimScape Multibody by MATLAB and comprise both mechanical and electrical domains. The performance of the models are validated against the performance of the robot when unloaded and loaded with a mechanical proxy for a human arm. The models were further validated against data from a human participant after satisfactory performance in the previous tests. The effects of the robot 's dynamics were observed similarly in the computational results of the modelling, the data from the human participant and patient testing data from a previous iteration of the robot.

It is demonstrated that the combination of SimScape and SimScape Multibody is an appropriate tool for building a multi-domain dynamic model of the robot and that this modelling method provides advantages over traditional robotic modelling approaches. It is demonstrated that the responses of the model match the responses of the physical robot with acceptable accuracy.

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TOPIC: Rehabilitation and assistive robotics

P-128

A Machine Learning Based Performance Classification for Post-Stroke Rehabilitation Using Kinematic Features

Dong, Shuhao 1; Levesley, Martin 1; Gallagher, Justin 1; Jackson, Andrew 1
1: University of Leeds

The recovery of post-stroke patients is dynamic, changing throughout the rehabilitation process. To achieve optimised rehabilitation intervention for individual patients with changing impairments, classification based on sensitive and continuous assessments of motor function is crucial. However, the existing categorical-score based clinical assessments are not sensitive enough to be capable of reflecting subtle improvement. In this study, a simulation of stroke patients' acceleration profiles during an upper limb exercise was made with adjustable factors, representing different severities of impairment. Three machine learning models, namely Support Vector Machine (SVM), Random Forest (RF) and K-Nearest Neighbours (KNN), were trained based on six kinematic assessment features calculated from the simulations above. Sample Entropy (SE), Dynamic Time Warping (DTW) distance, Number of Peaks (NoP), Spectral Entropy (SpE), Spectral Arc-Length (SpAL) and Spectral Complexity (SpC) were used to classify patients into different groups. The performance of SVM was higher ($F1=0.934$) than those of RN ($F1=0.913$) and KNN ($F1=0.846$). In addition, the mean absolute errors of both the SVM and the Gaussian regression model in predicting the adjustable factors were 0.346 and 0.199, respectively. Both classification and regression models were applied to experimental data as well. It was shown that the proposed machine learning models, based on the simulated data, provide a promising and reliable tool for classifying impairment and hence optimising individual rehabilitation intervention at different stages of recovery.

This work was supported by: University of Leeds, China Scholarship Council

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TOPIC: Robotics for clinical practice

P-129

A Novel Wheelchair Ergometer for Automatic Optimization of Seat Positions of Everyday-Life and Sports Wheelchairs

Wittmann, Frieder 1; Vermeulen, Joel 1; Davis, Kiara 1; Schuh, Marc 2; de Vries, Wiebe 3; Holliger, Axel 1; Wolf, Peter 1;

1: ETH Zurich, Sensory-Motor Systems Lab; 2: Orthotec AG; 3: Swiss Paraplegic Research

The seating position of wheelchair users has an influence on, e.g., load on the shoulder and aerodynamics. Therefore, seating position is crucial for wheelchair users both in everyday life and in sports. We propose a novel wheelchair ergometer, the ETH-WErgo, which allows the user to bring their own chair and then test various seating positions in a short amount of time, using an electronically adjustable platform with three degrees of freedom [1]. The wheels of the chair are removed, and the chair is positioned between two freestanding instrumented wheels. The three-dimensional contact forces and torques created by the hand, as well as the rotary position of the wheels are measured at 1 kHz hard real-time. The ergometer can also render inertia, aerodynamic and rolling resistance via an adjustable flywheel and an electric motor, both connected via a driving belt.

We evaluated our ergometer with an everyday user. The usual seating position, as well as, three vertical and three horizontal position changes at 5 cm increments were tested for a total of 280 pushes. Peak vertical push rim force (PVPF) - one of the few variables with a proven link to shoulder pathology [2,3] - had non-overlapping 95% confidence intervals. However, these findings were dependent on which of the various low pass filter proposed in the literature was applied. Thus, it seems that, despite its popularity, PVPF might not be a robust variable to estimate shoulder load.

We also evaluated the ergometer with a former 400m European Wheelchair Racing record holder, and co-author Marc Schuh, using his own racing chair and found, that at a steady speed of 20km/h, oxygen consumption was affected when changing the aerodynamic resistance rendered by the wheels, opening the door for optimization of wheelchair seating position for the individual athlete.

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This work was supported by: Swiss Paraplegic Research

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TOPIC: Human-machine interfaces in rehabilitation

P-130

Using Transfer Learning to Reduce the Burden of Training for Position-Aware Myoelectric Prosthetic Control

Williams, Heather E.1; Faridi, Pouria 1; Shehata, Ahmed W. 1; Hebert, Jacqueline S. 1; Pilarski, Patrick M. 1,2

1: University of Alberta, Edmonton, Canada; 2: Alberta Machine Intelligence Institute (Amii), Edmonton, Canada

Electromyography (EMG) signals are commonly used to control myoelectric prosthetic arms. Unfortunately, detected surface EMG control signals are often altered when a user's limb is used in a position different from that in which it was trained, a problem known as the "limb position effect" [1]. In our prior work, we showed that a recurrent convolutional neural network (RCNN) trained with EMG and inertial measurement unit (IMU) data from multiple limb positions can achieve a position-aware classification accuracy of 99% [2]. However, this solution requires prosthesis users to perform long, cumbersome training routines (in 4 limb positions) before device use [3].

Objective: In this work, we show how transfer learning could be used to mitigate this problem -- by pretraining a generalized RCNN-based classifier with data from multiple participants, then retraining it with a fraction of the otherwise required data from a new individual, while keeping the generalized model's knowledge.

Methods: EMG and IMU data were collected from 19 non-disabled participants wearing a Myo armband (Kitchener, Canada). Participants held 5-second isometric contractions of 5 wrist movements (rest, flexion, extension, pronation, supination) in 4 limb positions (1. arm at side, 2. elbow at 90°, 3. shoulder at 90°, 4. shoulder up at 45° from vertical). A generalized classifier, capable of classifying wrist movements across these limb positions, was trained with data from 18 participants and then retrained with a small amount of data from the 19th participant. The amount of required data was investigated by altering the number of limb positions and the time spent in each wrist movement.

Findings & Significance: Model retraining using 2 seconds of data from each of 5 wrist movements in only 3 limb positions (1, 2, & 4) yielded a classification accuracy of 95%. We successfully used transfer learning to reduce the required training routine duration of a position-aware RCNN-based classifier by 70%.

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Position-Aware Myoelectric Prosthetic Control using Recurrent Convolutional Neural Networks and Transfer Learning

Heather E. Williams, Pouria Faridi, Ahmed W. Shehata, Jacqueline S. Hebert, Patrick M. Pilarski

Introduction

A challenge to EMG-based myoelectric pattern recognition control (Fig 1) is the

"limb position effect" [1]

- Surface EMG signals are altered when a user attempts to use their prosthetic limb in a position different from that in which it was trained (Fig 2).
- A recurrent convolutional neural network, trained with EMG and inertial measurement unit (IMU) data from multiple limb positions, can achieve an offline classification accuracy of 99% [2]. However, this requires prosthesis users to perform a long training routine before they can use their device.
- Hypothesis: transfer learning can address this problem. A generalized classifier can be trained with the EMG and IMU data from multiple individuals, and a smaller amount of data from a new individual can be used to retrain the generalized model.

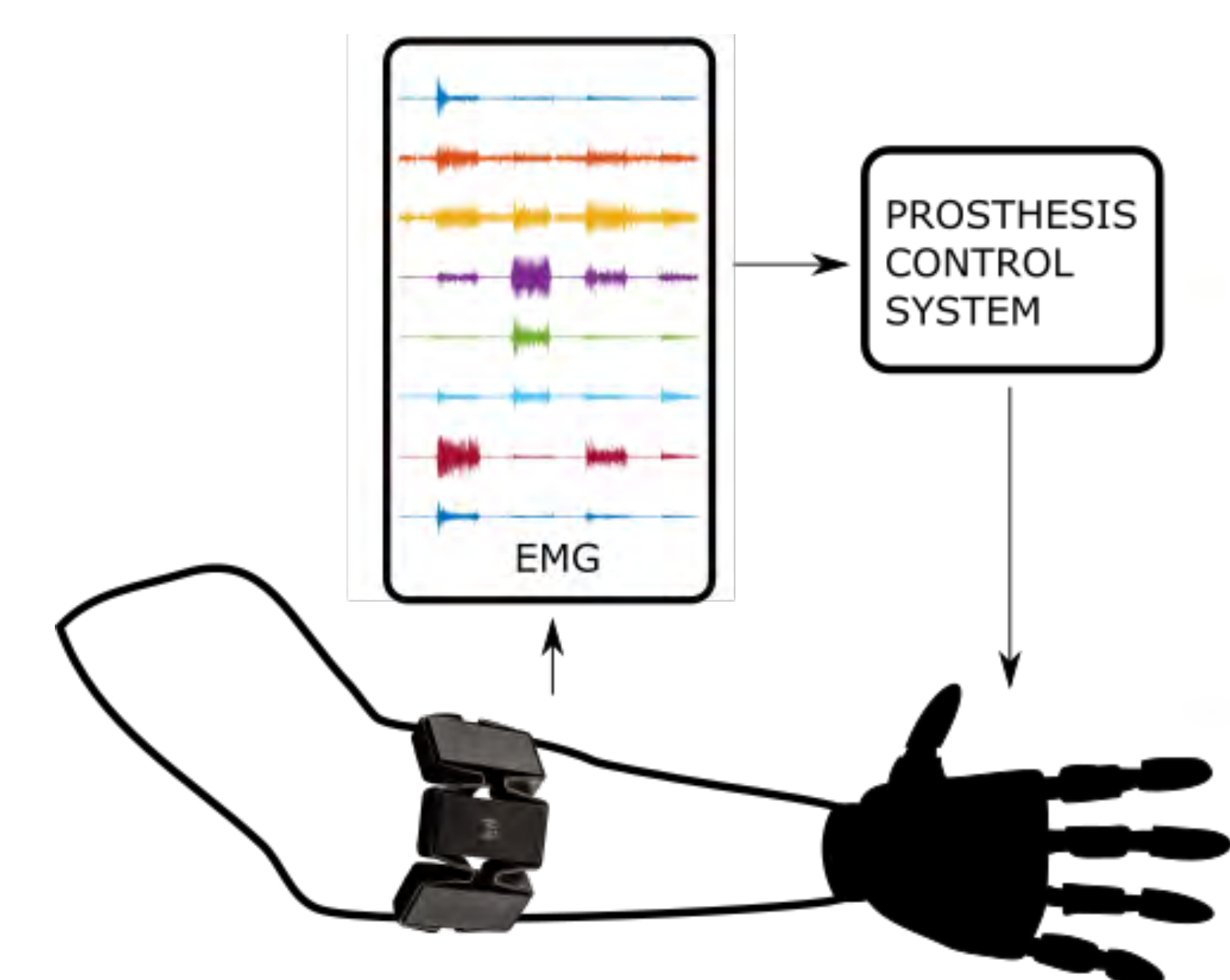


Fig 1. Myoelectric control

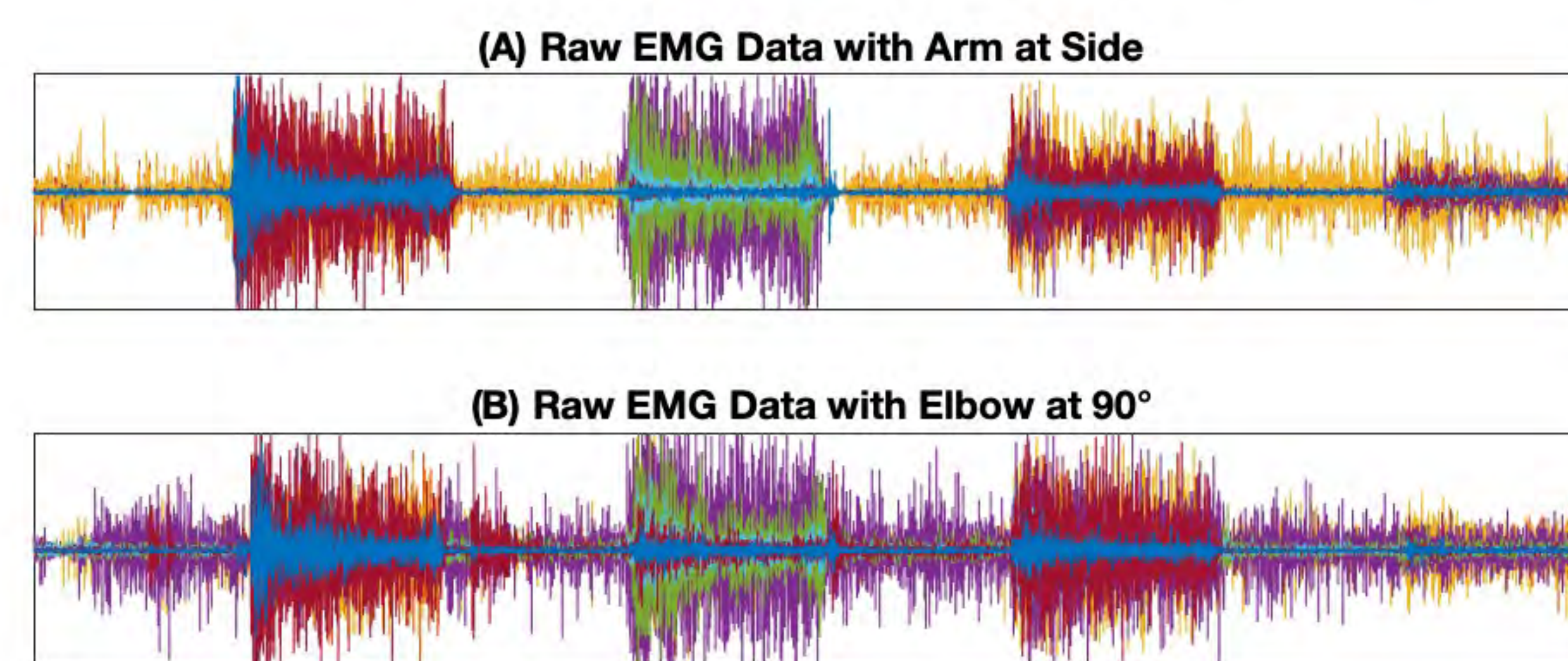


Fig 2. Raw EMG data at two limb positions: (A) arm at side, and (B) elbow at 90°

Methods

EMG and IMU data were collected from 16 non-disabled participants, using two Myo armbands (Fig 3A). Participants held isometric contractions of 5 wrist movements (Fig 3B), for 5 seconds each. Each wrist movement was repeated in 4 limb positions (Fig 3A). A generalized classifier was trained with data from 15 participants, and the model was subsequently retrained with data from the remaining participant.

Results

Retraining the generalized classifier with 2 seconds of data in each wrist movement and three limb positions provides accurate results (Fig 4). Specifically, training with the data from arm at side, elbow at 90°, and arm up at 45° yields **95.20%** accuracy.

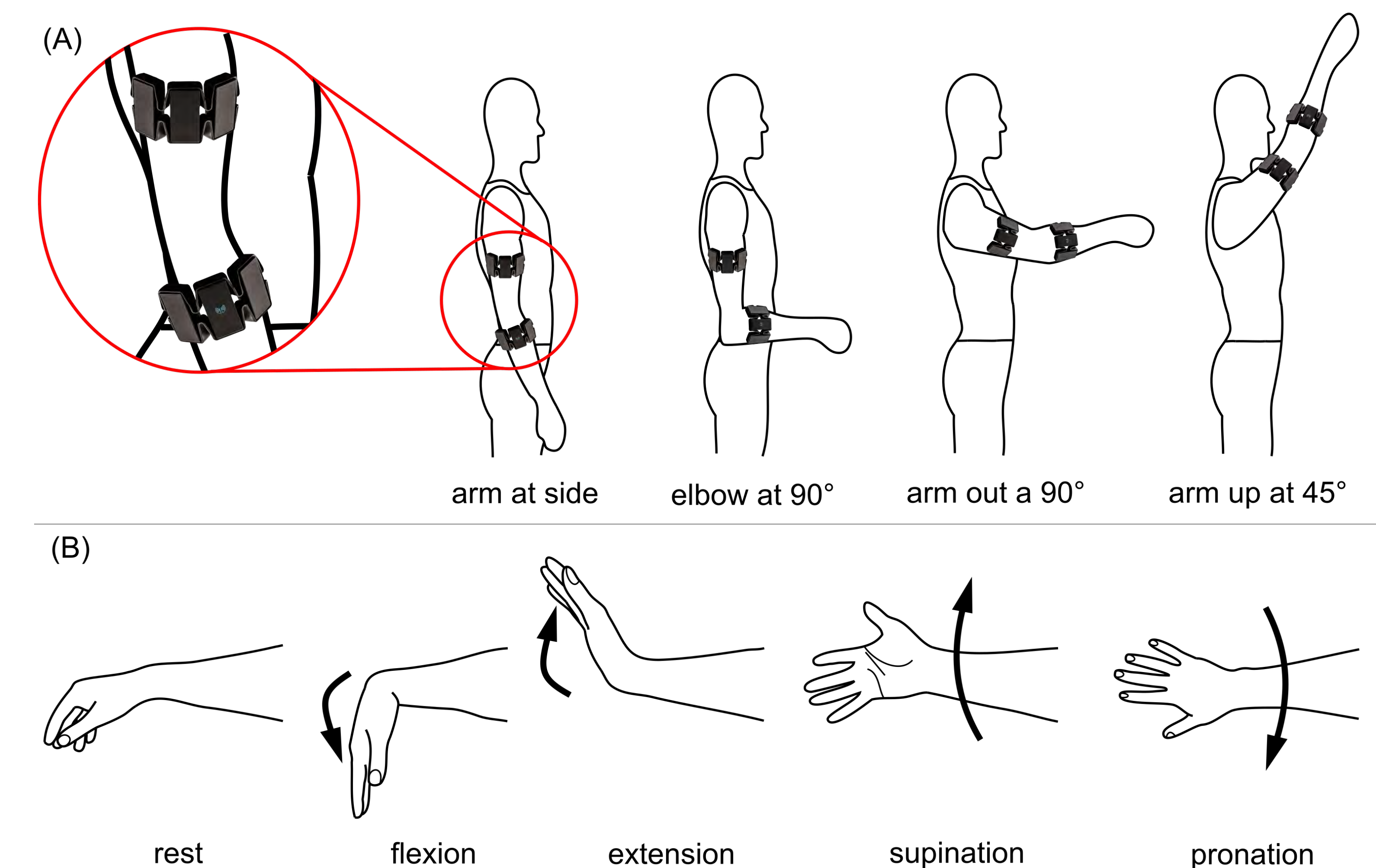


Fig 3. (A) The placement of each Myo armband, along with limb positions used in data collection, and (B) wrist movements used in data collection.

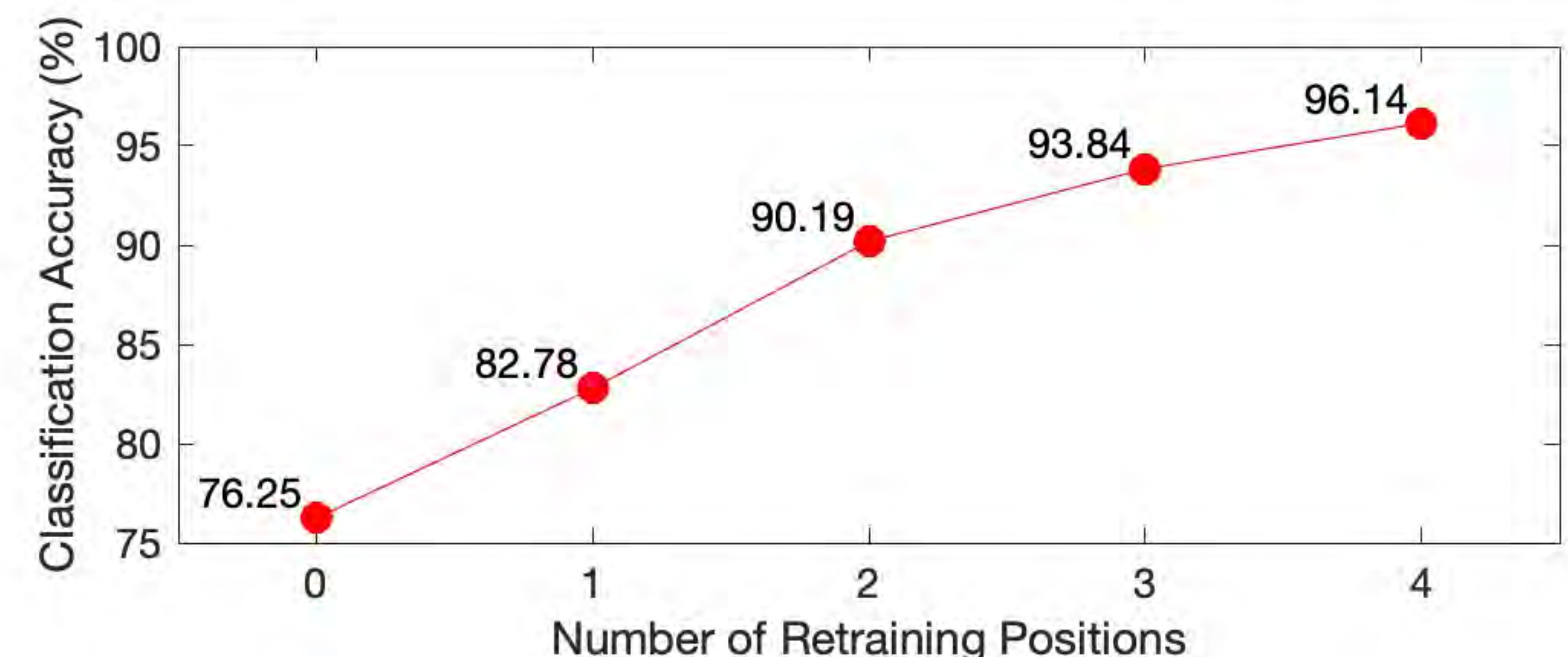


Fig 4. Average classification accuracy as a generalized model is retrained with data from a specified number of limb positions. 0 positions indicates that no transfer learning was used.

Discussion

- Transfer learning \Rightarrow training routine duration \downarrow and classification accuracy \uparrow
- A training routine in one limb position (with 5 secs for each wrist movement) would take at least 25 secs, but training in all 4 limb positions would take at least 100 secs. Instead, if the training routine required 2 sec for each wrist movement and 3 limb positions, it would reduce this training time to only 30 secs.
- Future steps will include real-time testing of a control strategy using the model proposed in this research.

[1] Gigli A, et al. *ICORR* 2019. 1061–6, 2019.

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TOPIC: Human-machine interfaces in rehabilitation

P-131

Functional Interaction of Objects During Myoelectric Control of a Prosthetic Hand with Non-Invasive Somatotopic Tactile Feedback

Vargas, Luis 1; Huang, He (Helen) 1; Zhu, Yong 2; Hu, Xiaogang

1: Joint Department of Biomedical Engineering at University of North Carolina at Chapel Hill and North Carolina State University, Chapel Hill/Raleigh, USA; 2: North Carolina State University, Raleigh, USA

Sensory feedback, especially tactile feedback of the hand, is critical for daily activities. During interaction with prosthetic limbs, a lack of tactile percepts can limit functionality of prosthesis utility. Prior work has shown that evoked tactile feedback can improve tactile perception, including object property recognition; however, few studies have assessed the functional benefits (e.g., object manipulation) when utilizing non-invasive somatotopic feedback. Accordingly, this study evaluated the performance of object manipulation during closed-loop control of a prosthetic hand. Tactile feedback was elicited through transcutaneous nerve stimulation from a multi-electrode array. The elicited tactile sensation along the hand encoded the prosthetic 's fingertip forces. Two controller strategies (position and velocity control) were employed. Myoelectric signals recorded during finger flexion and extension were used to modulate the prosthesis ' finger position or velocity. A modified box-and-block task was used to assess performance. Specifically, subjects grasped, lifted, held, and transported cubes of varying weights. Our results showed that tactile feedback reduced the average grip force by approximately 39% during the holding phase, and the grip force scaled with the object weight only when feedback was provided. The effort (cumulative muscle activation) required to complete the task varied depending on the controller type. Specifically, position control required more effort even when feedback was provided; however, the addition of feedback during velocity control appeared to reduce the effort required to complete the task. Lastly, the average completion time across subjects ranged from 5.3 to 6.3 seconds with the shortest completion time observed in velocity control with feedback on. The outcomes can help understand the sensorimotor integration processes in human-machine interactions.

This work was supported by: National Institute of Health (1 F31 NS110364-01A1)



TOPIC: Rehabilitation and assistive robotics

P-132

Implications of Fatigue on Wrist Stiffness and Position Sense

Falzarano, Valeria 1,2; Albanese, Giulia A. 1,2; Holmes, Michael W.R. 3; Morasso, Pietro 1; Zenzeri, Jacopo 1

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Fatigue is a condition associated with intense use of muscles, that leads to a decline in motor performance and a drop of muscle activity mean frequency[1]. Among the effects of fatigue, short-term changes in intrinsic biomechanical properties and proprioception in the wrist joint have never been investigated jointly. In our study, we developed a time-constrained protocol to assess if and for how long dynamic fatigue could influence wrist stiffness and position sense. The entire protocol was performed using a robotic device designed for the wrist joint[2]. The fatigue task consisted of a series of wrist movements with the target position at 45° of wrist flexion. A torque tailored to subjects' maximum isometric wrist flexion force opposed the motion. The end of the task was determined by a physiological threshold, given by a 40% decrease in the flexors mean frequency. To assess both stiffness and position sense, participants repeated the protocol in two different days. Each assessment was paired with the evaluation of their isometric forces and repeated once before the fatigue task and at 4 following time points. Proprioception was tested with an active position sense paradigm, during which 12 target positions in flexion were firstly haptically identified and then replicated. Wrist stiffness was measured through the delivery of small passive rotational perturbations along the wrist flexion-extension direction at $100^\circ/\text{s}$ velocity[3]. Our results suggest that both errors in replicating wrist positions and stiffness values were reduced immediately after the fatigue task. While inspecting the post-fatigue phase, both measures showed a tendency to reach pre-fatigue values. Because fatigue is a symptom of many neurological diseases, understanding how functional components of the wrist joint are affected by a fatigue task and their dynamic recovery could be critical to better understand how these populations might be affected during daily fatigue tasks and how to prevent it.

References: Mugnosso, Maddalena, Francesca Marini, Michael Holmes, Pietro Morasso, and Jacopo Zenzeri. 2018. "Muscle Fatigue Assessment during Robot-Mediated Movements." *Journal of NeuroEngineering and Rehabilitation* 15 (1): 119. <https://doi.org/10.1186/s12984-018-0463-y>. Iandolo, Riccardo, Francesca Marini, Marianna Semprini, Matteo Laffranchi, Maddalena Mugnosso, Amel Cherif, Lorenzo De Michieli, Michela Chiappalone, and Jacopo Zenzeri. 2019. "Perspectives and Challenges in Robotic Neurorehabilitation." *Applied Sciences (Switzerland)* 9 (15). <https://doi.org/10.3390/app9153183>. Falzarano, Valeria, Giulia Petrella, Francesca Marini, Michael W.R. Holmes, Lorenzo Masia, Pietro Morasso, and Jacopo Zenzeri. 2020. "Preliminary Evaluation of a Robotic Measurement System for the Assessment of Wrist Joint Spasticity." *Proceedings of*

Implications of Dynamic fatigue on Wrist Stiffness and Position Sense

Valeria Falzarano^{1,2,+}, Giulia A. Albanese^{1,2,+}, Michael W.R. Holmes³, Pietro Morasso¹ and Jacopo Zenzeri¹

¹Robotics, Brain and Cognitive Sciences Department, Istituto italiano di tecnologia, Genova, Italy

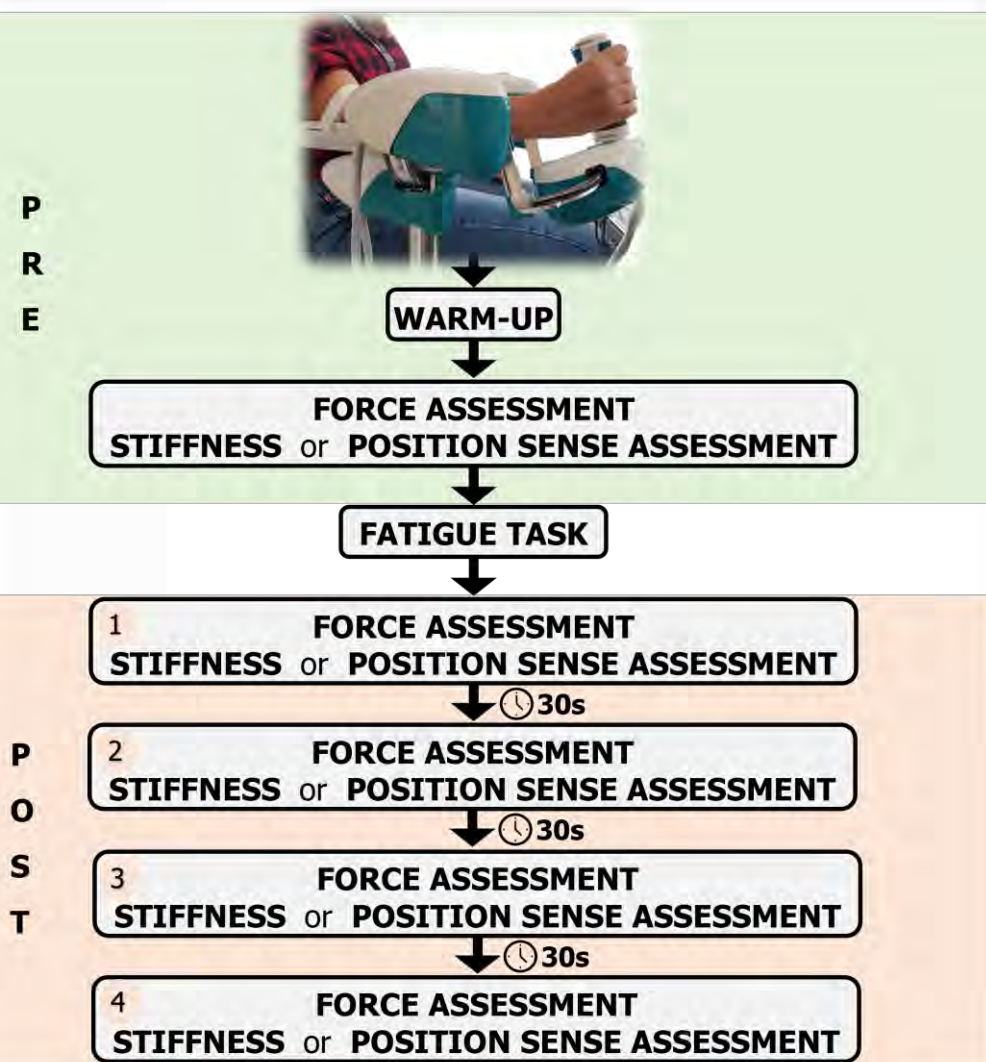
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³Faculty of Applied Health Sciences, Brock University, St. Catharines, ON, Canada

MOTIVATION and BACKGROUND

Fatigue is a temporary condition associated with intense muscle use. A drop in the mean frequency of electromyographic signals is an indicator of fatigue. Short-term changes in biomechanical properties and proprioception in the wrist joint have never been investigated. In our study, we developed a time-constrained robotic protocol to assess *if and for how long dynamic fatigue could influence wrist stiffness and position sense*.

EXPERIMENTAL PROTOCOL



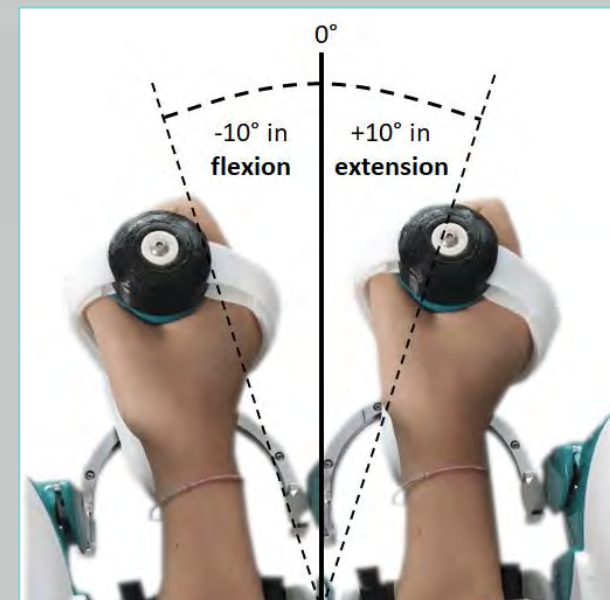
FORCE ASSESSMENT: Grip force and isometric wrist forces (flexion/extension) evaluated using the robot.

METHODS

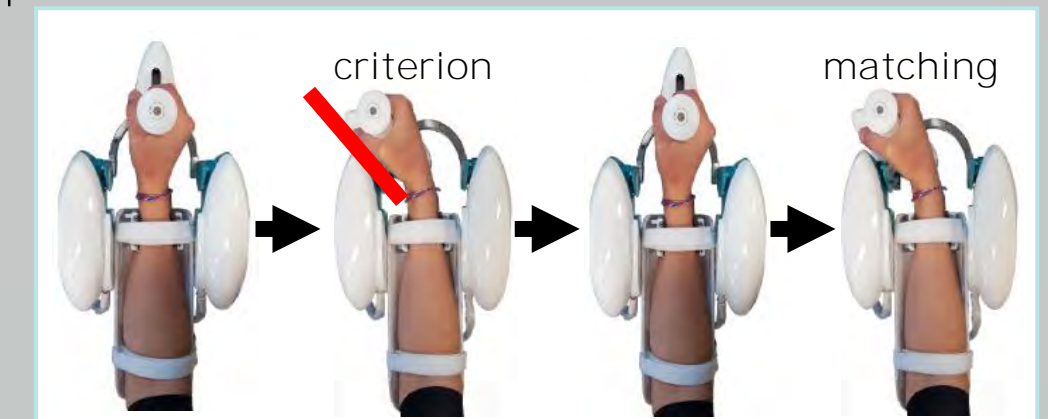
STIFFNESS or POSITION SENSE ASSESSMENT

The *WristBot*, a 3 degrees of freedom manipulum, delivered small amplitude ($\pm 20^\circ$) and quick rotational displacements along flexion-extension direction of the human wrist. Stiffness (K) was computed by a linear mass-spring-damper model

$$\tau(t) = I\ddot{\theta}(t) + B\dot{\theta}(t) + K\theta(t)$$



Position sense was tested with an active paradigm and targets ($15^\circ \pm 1^\circ$) were perceived as virtual walls.

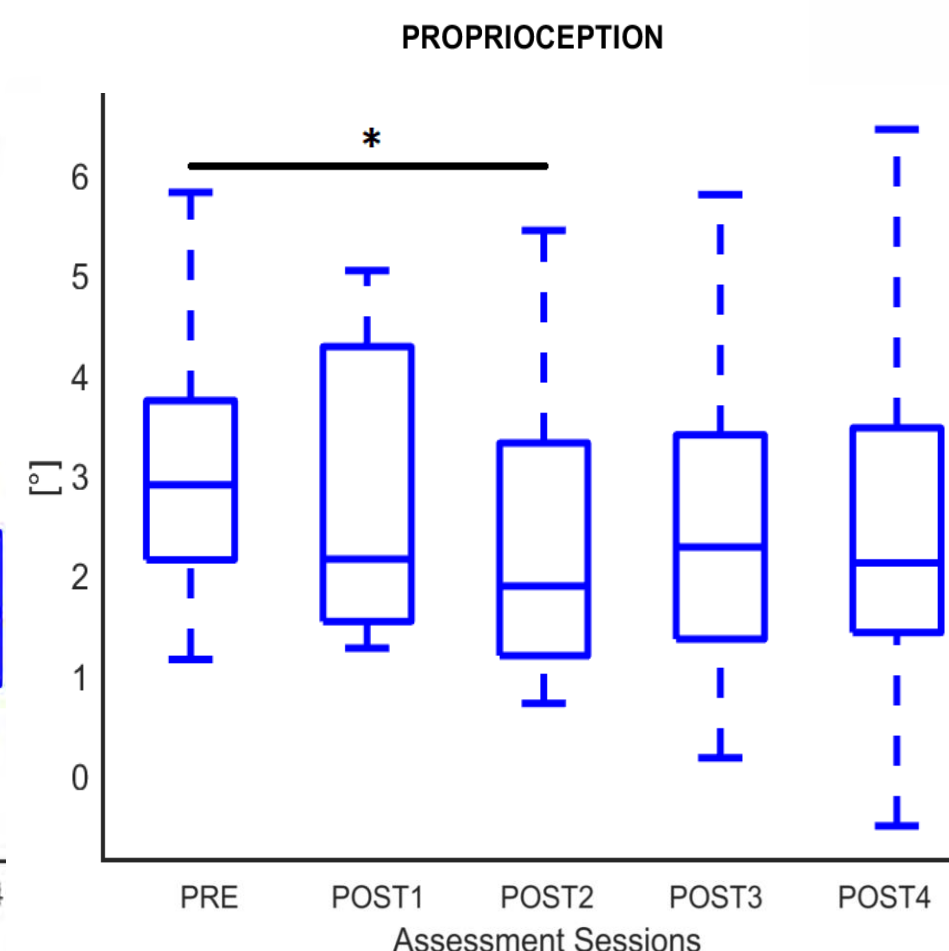
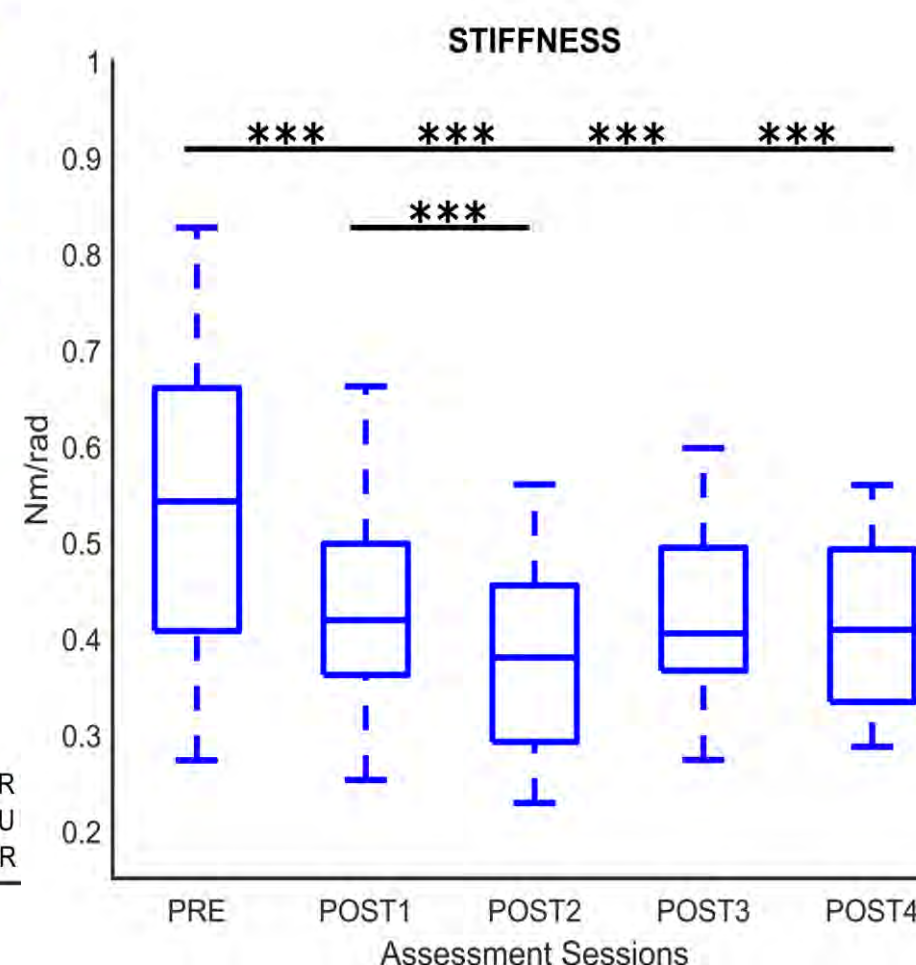
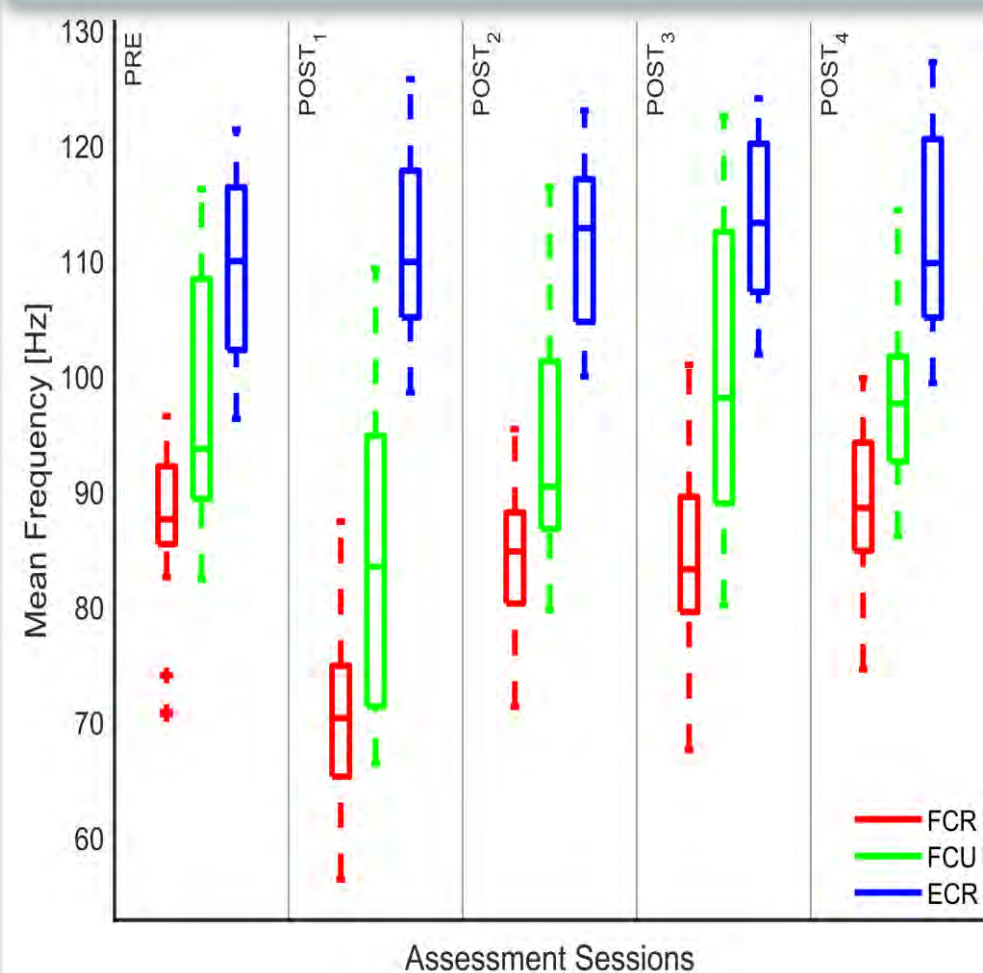


DYNAMIC FATIGUE TASK

Series of reaching movements from the neutral position toward flexion. A torque (60% of each subject maximum isometric wrist force in flexion) resisted to **subjects'** movements toward flexion and facilitate those toward extension.

A real-time algorithm detected the fatigue state: the fatigue task terminated when the mean frequency of either Flexor Carpi Radialis (FCR) or Flexor Carpi Ulnaris (FCU) sEMG signal shift toward lower frequencies (40% decrease).

RESULTS



CONCLUSIONS

Since *early onset of fatigue is a common symptom of many neurological diseases*, understanding its implications on wrist functionality could be crucial in rehabilitation. In our work, we presented a conditions- and time-controlled experimental assessment protocol, performed entirely using a robotic device. sEMG was added to assure a comparable state of muscle fatigue among subjects.

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TOPIC: Rehabilitation and assistive robotics

P-133

Compliant motion planning and intelligent postural stability for lower-limb exoskeletons

Mehr, Javad K. 1,2,3; Sharifi, Mojtaba 1,2,3; Mushahwar, Vivian 2,3; Tavakoli, Mahdi 1,3

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2: Division of Physical Medicine & Rehabilitation, Department of Medicine, University of Alberta, Edmonton, Alberta, Canada;

3: Sensory Motor Adaptive Rehabilitation Technology (SMART) Network, University of Alberta, Edmonton, Alberta, Canada;

Due to the difference in the gait patterns of people, it is necessary to make the exoskeletons more adaptive and compliant to human interaction than they currently are. However, providing shapeable trajectories for the exoskeleton joints can lead to safety problems such as losing postural stability. To address this issue, an intelligent control strategy was developed for both trajectory planning and postural stability by sharing authority between the human and lower-limb exoskeleton. Divergent component of motion (DCM) analysis was proposed based on the linear inverted pendulum flywheel model (LIPFM) for position adjustment of the center of mass (CoM) in humanoid robots [1]. In this study, the LIPFM was replaced with a new four-degree-of-freedom model which can be personalized for each user by relaxing the assumption of having the CoM fixed at the hip joint as has been the case in the previous LIPFM. The extended DCM analysis used in this study was based on the new model for monitoring and regulation of the CoM position for multi-DOF exoskeletons. The model was tested by a neurologically-intact person and results demonstrated that the exoskeleton has the autonomy to ensure postural stability and viability of locomotion in a compliant human-robot interaction. To facilitate enough authority for the exoskeleton's wearer to modify the motion trajectories, adaptive central pattern generators (CPGs) were utilized. Given the CPGs, the subjects could modify the amplitude and frequency of walking from the initial values to generate their desired gait patterns by applying interaction torque to the exoskeleton. Collectively, the proposed intelligent control strategy can enhance human safety and comfort by offering an appropriate trade-off between robot autonomy and human authority.

References: [1] Jeong, Hyobin, et al. "A robust walking controller based on online optimization of ankle, hip, and stepping strategies." IEEE Transactions on Robotics 35.6 (2019): 1367-1386.

This work was supported by: Canada Foundation for Innovation (CFI),
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Compliant motion planning and intelligent postural stability for lower-limb exoskeletons

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INTRODUCTION

The overall goal of this project is to develop an intelligent control strategy which can provide a safe and compliant walking pattern for lower-limb exoskeleton users.

Motivations

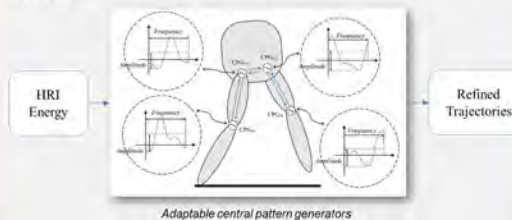
- People have different gait patterns. Amplitude, frequency and range of motion for joints vary from one person to another one.
- To provide comfortable walking, exoskeleton trajectories need to be adaptable with a user's gait pattern.
- To guarantee the safety of the user, postural stability needs to be monitored while letting the user reshape the exoskeleton joints' trajectory.

METHODS

An adaptable central pattern generator (CPG) method and a divergent component of motion (DCM) analysis are employed to reshape the trajectories and enhance postural stability, respectively.

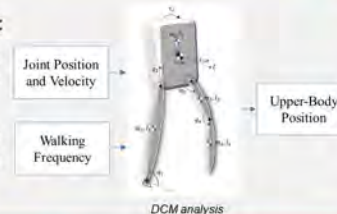
Adaptable Central Pattern Generators (A-CPGs):

- CPGs are a set of differential equations for amplitude, frequency and phase that can produce time-continuous rhythmic motions.
- In the adaptable CPGs, the human-robot interaction energy is embedded in the amplitude and frequency equations to translate users' interaction to their desired walking pattern.
- Human-robot interaction (HRI) energy is estimated by neural networks.



Divergent Component of Motion (DCM):

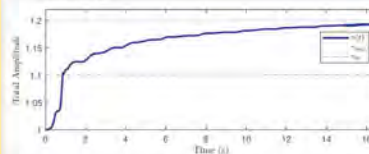
- DCM represents the dynamics of motion for center of mass for the human-exoskeleton system.
- DCM analysis is employed to modify the trajectory of the hip joint of the stance leg to adjust the upper body position.



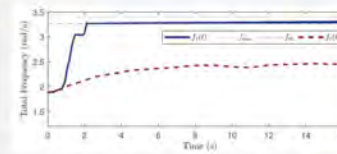
RESULTS

Results for the A-CPGs

- The adaptable CPGs could update the amplitude and frequency of walking continuously based on the user's interaction with the exoskeleton.
- The solid blue lines show the results for the case that the user has increased amplitude and frequency up to the maximum values.
- The dashed red line in the frequency plot shows the result for the case that user has increased the velocity and kept it below the maximum value in the rest of walking.



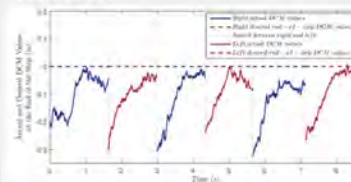
Variations of the amplitude via A-CPGs



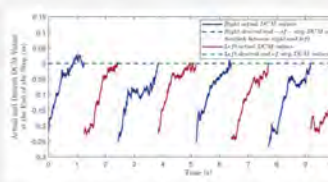
Variations of the frequency via A-CPGs

Results for the DCM analysis

- DCM trajectories in the absence and presence of the upper-body position corrections:

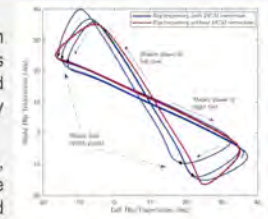


DCM trajectory and the desired DCM at the end of each step without DCM corrections



DCM trajectory and the desired DCM at the end of each step with DCM corrections

- Synchronization between the right and left hip joints in the presence and absence of the upper-body position adjustments.
- The points on the figure, show the stance phase switches between right and left legs.



Synchronization of the right and left hips with and without DCM correction

DISCUSSION

- User could increase/decrease the amplitude and frequency of walking by applying assistive/resistive torques. Note that this increment was limited to safe ranges.
- The upper-body adjustment was effective in decreasing the error between the desired and actual values of the DCM at the end of each step.
- By applying the upper-body position adjustments via DCM analysis, the DCM trajectory over different steps has become more organized in comparison with the case of no corrections.
- The corrections applied to the hip joints resulted in the phase adjustment between right and left hip trajectories. The corrections have been applied to push the upper-body forward in response to the users' velocity increasing.

CONCLUSION

- A shared autonomy approach was suggested for the control of lower-limb exoskeletons, which gave the user enough authority to adjust the exoskeleton's walking pattern. In response to human interaction, the exoskeleton automatically adjusted the upper-body position to enhance postural stability.
- Given the proposed intelligent control strategy, walking will be more adjustable for each exoskeleton wearer with safety improvement.

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TOPIC: Human-machine interfaces in rehabilitation

P-134

Adaptive Virtual Reality-based Rehabilitation in Children with Cerebral Palsy: A proof-of-concept

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1: Institute of Clinical Physiology (IFC), National Research Council (CNR), Pisa, Italy; 2: Institute of Mechanical Intelligence, Scuola Superiore Sant'Anna, Pisa, Italy; 3: Unit of Neurocognitive Rehabilitation for Developmental Ages, University Hospital of Pisa (AOUP), Pisa, Italy; 4: Rehabilitation Unit, Ospedale della Versilia, Viareggio, Italy

The new global estimates establish rehabilitation as a key strategy for Universal Health Coverage in the 21st century. Rehabilitation is essential in addressing the full scope of health needs of a population, especially during developmental disabilities that affect about 1 in 6 (17%) children aged 3-17 years [1]. Treatment options for developmental disabilities are broad ranging but often therapeutically ineffective. Future rehabilitation methods should tailor the therapy to the patient, based on its individual phenotypic characteristics and the evolution of treatment response (personalized medicine) [2].

The present “proof-of-concept” proposes an innovative rehabilitation strategy based on continuous data monitoring and analysis, in order to adapt the proposed therapeutic sessions to the real abilities of the children with neuromotor impairments.

We made use of the latest ground-breaking VR technologies released in 2020: Head Mounted Displays (HMD) with embedded computer graphic processing and embedded position tracking, combined with custom designed, compliant haptic devices worn at the hand [3]. Gaming scenarios include rehabilitation exercises fully interfaced with the provided kinematic parameters, and based on trajectory tracking, finalized reach-to grasp tasks, and control of body balance. AI algorithms for data processing and adaptation (trajectories identification and kinesiological data analysis) are processed on-board the device. A compelling narrative background is enclosed: the child plays as a wizard apprentice, requiring motor and cognitive learning to cast the more complex and powerful spells.

Combination of the two approaches (serious games and data monitoring) will fully exploit the potential of tailoring the therapy to the patient, within an effective, flexible, and repeatable rehabilitation system. Together with the proposed technologies, it aims to foster the development of robust and easy-to-use home-care rehabilitation solutions.

References: Zablotsky, B., Black, L. I., Maenner, M. J., Schieve, L. A., Danielson, M. L., Bitsko, R. H., ... & Boyle, C. A. (2019). Prevalence and trends of developmental disabilities among children in the United States: 2009-2017. *Pediatrics*, 144(4)., Zahabi, M., & Abdul Razak, A. M. (2020). Adaptive virtual reality-based training: a systematic literature review and framework. *Virtual Reality*, 24(4)., Bortone, I., Barsotti, M., Leonardis, D., Crecchi, A., Tozzini, A., Bonfiglio, L., & Frisoli, A. (2020). Immersive Virtual

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Environments and Wearable Haptic Devices in rehabilitation of children with neuromotor impairments:
a single-blind randomized contro

This work was supported by: Bando regionale Ricerca Salute 2018 - Progetto TELOS "Tailored neurorehabilitation thErapy via multi-domain data anaLytics and adaptive seriOus games for children with cerebral palsy" (CUP J52F20001040002)

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TOPIC: Rehabilitation and assistive robotics

P-135

Design, Analysis, Development, and EMG-Based Control of an Upper-Limb Exoskeleton with Soft Artificial Muscles

Sharifi, Mojtaba 1,2,3; Mehr, Javad K. 1,2,3; Hao Fan 1; Vicky Chen 1; Marcos H. Diaz 1; Mushahwar, Vivian 2,3; Tavakoli, Mahdi 1,3

1: Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta, Canada;

2: Division of Physical Medicine & Rehabilitation, Department of Medicine, University of Alberta, Edmonton, Alberta, Canada;

3: Sensory Motor Adaptive Rehabilitation Technology (SMART) Network, University of Alberta, Edmonton, Alberta, Canada;

Soft actuators and light structures have been recently deployed in medical robots and assistive mechatronic systems to enhance the safety and compliance of these systems' interaction with humans. In this study, a new soft-rigid exoskeleton for the upper extremity was designed, analyzed, and fabricated, and a control system was developed. McKibben pneumatic artificial muscles were utilized as soft actuators, and cable-driven force transmission and lightweight 3D-printed and CNC-machined components were used to physically couple the exoskeleton with the human body and assist the movement of the arm. This assistive mechatronic system was specifically developed to support the shoulder and elbow joints to facilitate major movements of the arm in 3D space. Structural design and stress-strain analyses were obtained for the whole system as well as each part of the exoskeleton. A new mathematical model for the artificial muscles was derived, and the parameters of this model were identified using various experiments. A motion planning strategy and a position controller with gravity compensation were implemented by incorporating electromyography (EMG) signals from medial deltoid, anterior deltoid, and biceps brachii muscles and the soft actuator model. The EMG-based controller moved the arm and the exoskeleton based on the users' intention, which was interpreted from their muscle activity level, and assisted them in accomplishing manual tasks with less muscle effort. The experimental studies were conducted with an able-bodied wearer in a weight handling task and demonstrated the assistive action of the exoskeleton. Compared to the no-assistance trials, muscle activation in the upper limb was reduced by more than 67% during the task. Future extensions of the work will include the fabrication of an industrial version of the exoskeleton to assist workers in their heavy manual tasks with adjustable features in its structure and intelligent torque control.

This work was supported by: Canada Foundation for Innovation (CFI),
Natural Sciences and Engineering Research Council (NSERC) of Canada,

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Canadian Institutes of Health Research (CIHR),

ST Innovations, SMART Network, University of Alberta,

Alberta Jobs, Economy and Innovation Ministry 's Major Initiatives Fund to the Center for Autonomous Systems in Strengthening Future Communities.

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TOPIC: Rehabilitation and assistive robotics

P-136

Design and Kinematic Modeling of a Novel Cable-Driven Shoulder-Elbow Exoskeleton

Ahmad Zahedi 1,2; Yansong Wang 2; Dingguo Zhang 3

1: Robotics Institute, Shanghai Jiao Tong University, China; 2: Robotics Institute, Shanghai Jiao Tong University, China 3: Department of Electronic & Electrical Engineering, University of Bath, UK

In recent studies, portable exoskeletons for rehabilitation have been further developed in comparison with the different classifications of the exoskeleton such as haptic, assistive device, teleoperations, and power augmentation. Although existing devices with rigid actuators on human arm joints as power generators have been investigated to gain a more accurate motion position, high response frequency, and easier trajectory for tracking control. However, there are some drawbacks like bulky structures and high weight which make limitations in interacting with the user such as low portability and a lack of patient acceptance. In order to overcome the mentioned shortcomings, a novel fully portable cable-driven exoskeleton system for upper limb rehabilitation has been proposed which has outstanding benefits include low mass and inertia, human-robot interaction (HRI), acceptable range of motion (ROM), remarkable strength, quick adjustability, and not restricted by the bulky structure. The links of the cable-driven exoskeleton system is inspired by the Bamboo structure which the cables are routed between human joints and actuators through these links. The exoskeleton system is named Portable Bamboo-Inspired Exoskeleton (PBIE) which assist the movement of shoulder and elbow joints. The COMSOL software was performed to determine the high buckling strength of the Bamboo inspired links of the PBIE system in comparison to the ordinary carbon-fibre tube. In addition, the kinematic configuration was modelled by the modified Denavit-Hartenberg (D-H) notation, the verification experiment was carried out by tracking the trajectory in Cartesian space after the prototype was developed. Through experiments, it can be observed that the backlash is about 0.06 rad or about 3° . Comparing the distance between the 3D trajectory and the center of the circle with the reference radius, the MAE is 5.9 mm and the RMSE is 6 mm so that the relative error is about 11.8%.

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TOPIC: Rehabilitation and assistive robotics

P-137

Novel Multilayer Perceptron Based Controller for Precise Delivery of Exoskeleton Assistance during Walking

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Children with cerebral palsy (CP) can have variable gait patterns which make exoskeleton controller design challenging. Hierarchical approaches, including finite state machines (FSMs), that segment the gait cycle into smaller phases provide consistency and have resulted in improved posture in children with CP [1]. Yet tuning an FSM is challenging, time consuming and presents a barrier to clinical deployment. Multilayer perceptron (MLP) is a deep learning method that can be a solution to this problem. Here, we develop a novel MLP based controller to segment the gait cycle automatically using data from exoskeleton sensors. This approach retains the clinical utility of an FSM by allowing exoskeleton assistance to be specified during each gait phase, without the necessary step of tuning.

To establish the feasibility of this approach, we analyzed previously collected data from one participant with CP walking with the NIH P.REX exoskeleton [1]. The participant was 13 years old and was assessed as GMFCS III [2]. Informed consent was obtained prior to participation in our protocol that included 9 walking sessions. The MLP algorithm was trained on the first 60 secs of exoskeleton sensor data (joint angle and angular velocity from the encoder, foot ground contact from the force sensitive resistor) using the Adam optimization method [3]. MLP accuracy was assessed offline using the true positive rate for applying knee extension assistance torque during early stance, mid-stance and late swing phases and turning off assistance during late stance and early swing over 32 trials (lasting 96 secs on average) across 9 sessions.

Mean MLP accuracy across all sessions was 82% and 79% for the right and left legs, respectively. These results demonstrate that an MLP based controller is capable of providing assistive torque during discrete gait phases with minimal training and no manual tuning. Future work will focus on increasing accuracy and real time implementation.

References: J. Chen, J. Hochstein, C. Kim, L. Tucker, L. E. Hammel, D. L. Damiano, T. C. Bulea, A pediatric knee exoskeleton with real-time adaptive control for overground walking in ambulatory individuals with cerebral palsy, *Front. Robot. AI*, 8 (2021) 173., R. Palisano, P. Rosenbaum, S. Walter, D. Russell, E. Wood, B. Galuppi, Gross motor function classification system for cerebral palsy, *Dev. Med. Child Neurol*, 39 (4) (1997) 214-23., D. P. Kingma, J. Ba, Adam: A method for stochastic optimization, *arXiv preprint arXiv:1412.6980* (2014).

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This work was supported by: This research was supported by the Intramural Research Program of the NIH Clinical Center.

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TOPIC: Rehabilitation and assistive robotics

P-138

Rehabilitation Training Under Gravity Compensation with Harmony Exoskeleton Improves in Movement Quality for Individuals with Chronic Stroke

Hailey, Rhet O.1; de Oliveira, Ana C.2; Ghonasgi, Keya2; Rose, Chad G.1; Deshpande, Ashish D. 2
1: Auburn University, Auburn, AL, USA; 2: University of Texas at Austin, Austin, TX, USA

While robot assisted therapy for upper extremity has shown promise towards improving motor function for stroke patients, training modalities offered by the prior robotic systems are limited. Recently developed Harmony exoskeleton offers support for training a wide range of arm movements, maintains proper shoulder support, records movement and effort data, and affords both position and force control allowing for on-demand modulation of interaction dynamics. In this study, we examined the impact of training mediated by Harmony on the recovery of upper-body movement quality of stroke patients, including range of motion, movement smoothness, and spatial awareness of the arm [1]. Four participants with chronic stroke took part in seven one-hour training sessions along with pre- and post-assessment sessions. During each training session, there were two categories of movements: six sets of passive-stretching exercises and six sets of exercises using gravity compensation [2]. Pre- and post-study sessions contained three different tasks performed with and without gravity assistance, and ground-truth measurements were taken with an optical motion capture. The three assessment tasks performed were: (1) reaching to three points along a line in the horizontal plane, (2) matching an arm pose from the contralateral to the ipsilateral side only using proprioception, and (3) recreating the six training exercises. In this poster, we present changes in the performance of these assessment tasks, specifically movement smoothness (spectral arc length), spatial awareness (accuracy of proprioception), and coordination (reaching movement efficiency) arising from interactions with Harmony exoskeleton [3]. The promising results of the impact of gravity compensation and coordinated movement training will guide the design of future interventions and assessments.

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This work was supported by: National Science Foundation, Mission Connect, a project of the TIRR Foundation, CAPES (Brazil), Auburn University Samuel Ginn College of Engineering

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TOPIC: Computational neurorehabilitation

P-139

Operant conditioning of monosynaptic spinal reflexes: a simulated environment approach

Kim, Kyoungsoon 1; Oblak, Ethan 2; Schweighofer, Nicolas³; Sulzer, James 1

1: University of Texas at Austin, Texas, USA; 2: RIKEN institute, Japan; 3: University of Southern California, California, USA

Operant conditioning of neural activation suffers from a high incidence of non-responders. Delineating the cognitive response to feedback can help determine why some individuals, especially those with cognitive impairment, may not respond to neurofeedback training. We developed a simulated operant H-reflex conditioning neurofeedback environment that separated the ability to self-regulate the neurofeedback signal from its perception by using an explicit, unskilled visuomotor task. Our goal was to determine how feedback type, signal quality and success threshold affect operant conditioning performance and operant strategy. Subjects ($n = 40$) were instructed to play a web-app using keyboard inputs to rotate a virtual knob representative of an operant strategy. The goal was to align the knob with a hidden target. Participants were asked to “down-condition” the virtual feedback signal, which was achieved by placing the knob as close as possible to the hidden target. We presented feedback in terms of knowledge of performance (Kp), a bar height proportional to the distance to the target, and knowledge of results (Kr) where only the bar color changed when the feedback signal was below a threshold. Participants were exposed to ten conditions in two 2x3 study designs: 1) low/high variance and three feedback (Kp, Kr, and KpKr), 2) low/high variance and three thresholds (L/M/H) during Kr only. Each condition was presented 10 times in pseudorandom order in blocks of 35 trials. Our main outcomes were the feedback signal amplitude (performance) and the mean change in dial position (operant strategy). Results show that variability modulates performance and strategy depending on feedback type. These results show complex relations between fundamental feedback parameters and provides the initiatives for optimizing neurofeedback training for non-responders.

This work was supported by: NM4R

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TOPIC: Computational neurorehabilitation

P-140

Changes in Resting State Functional Connectivity Associated with Dynamic Adaptation of the Wrist

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Dynamic adaptation is an error-driven process of adjusting our planned motor actions to changes in task dynamics. Adapted motor plans are consolidated into motor memories that contribute to better performance on re-exposure to the same dynamic condition [1]. In parallel, dynamic perturbations can be compensated for by alternate motor control processes, such as co-contraction, that contribute to error reduction [2]. Whether these motor control strategies share the same neural resources for memory formation is unclear. To address this, we used an fMRI-compatible wrist robot, the MR-SoftWrist, to identify neural processes specific to dynamic adaptation and subsequent motor memory formation [3].

Using the MR-SoftWrist, 30 healthy adults performed a wrist pointing task in a zero force (control) condition and in a lateral force (adaptation) condition during fMRI to localize task-related brain networks. Resting state fMRI scans were acquired immediately pre- and post-performance of both tasks to quantify changes in resting state functional connectivity (rsFC) within these networks. We assessed behavioral retention of training 24 hours later. A variance decomposition analysis was used to isolate behavior associated with adaptation versus alternate error reduction strategies.

After the lateral force task, rsFC significantly changed in two brain networks: rsFC increased in the cortico-thalamic-cerebellar (CTC) network of the trained wrist and decreased interhemispherically within the cortical sensorimotor (SM) network. Linear regression analysis between rsFC and behavior returned significant associations between rsFC within the SM network and error reduction, and between rsFC within the CTC network and initial adaptation and retention, indicative of memory formation. Variance decomposition analysis indicated that rsFC within the CTC network is associated with adaptation, while decreases in rsFC within the SM network were associated with alternate error reduction processes.

References: Shadmehr, Reza. (2017). Learning to Predict and Control the Physics of Our Movements. *The Journal of Neuroscience*, 37(7), 1663-1671. <https://doi.org/10.1523/JNEUROSCI.1675-16.2016>, Franklin, D. W., Osu, R., Burdet, E., Kawato, M., & Milner, T. E. (2003). Adaptation to Stable and Unstable Dynamics Achieved by Combined Impedance Control and Inverse Dynamics Model. *Journal of Neurophysiology*, 90(5), 3270-3282. <https://doi.org/10.1152/jn.01112.2002>, Erwin, A., O'Malley, M. K., Rens, D., & Sergi, F. (2017). Kinesthetic Feedback during 2DOF Wrist Movements via a Novel MR-Compatible Robot. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 25(9), 1489-1499. <https://doi.org/10.1109/T>

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TOPIC: Rehabilitation and assistive robotics

P-141

Human-in-the-Loop Optimization of Hip and Knee Assistance for Downhill Walking with the Myosuit

Bergmann, Lukas 1; Koginov, Gleb 2; Leonhardt, Steffen 1; Riener, Robert 2; Xiloyannis, Michele 2
1: RWTH Aachen University, Aachen, Germany; 2: ETH Zurich, Zurich, Switzerland

Recent developments in the field of soft-robotic exoskeletons have brought such devices a step closer to being beneficial for both, people with gait impairments and those with physiological gait patterns [1]. With the wider adoption of this technology in everyday life, personalized timing and magnitude of assistance become crucial for support in unstructured environments.

We applied a method for determining individual assistance trajectories for downhill walking based on human-in-the-loop optimization. The developed optimization procedure is tested using the Myosuit - a tendon-driven soft robot for mobility assistance. The Myosuit supports weight-bearing of the hip and knee joint in the stance phase by applying a force through compliant tendons.

We derived a model-based trajectory by utilizing the joint torques found by Nuckols et al in [2] and used it as a reference model. The model can be characterized by the timing and magnitude of two peak values. Similar to [3], the covariance matrix adaptation evolution strategy algorithm (CMA-ES) and spline interpolation were applied to vary the parameter set and find assistance profiles minimizing the muscle activity. For this, the root-mean-square error of the averaged electromyogram of upper leg muscle groups was used as the cost function for the CMA-ES algorithm.

We derived and analyzed the generalized trajectories based on the individual support trajectories for each subject in eccentric movements. The first optimization experiments were carried out on healthy participants on a treadmill with a descending slope of ten degrees. Results have shown that a timely applied assistance force decreases muscle activity of knee extensors. As a next step, we will derive and evaluate the generalized optimization trajectories by comparing the subject's metabolic cost, muscle activity, and lower limb kinematics. Our long-term goal is to define a standardized method for determining optimal support for different slopes and gait pattern.

References: Xiloyannis, M., Alicea, R., Georgarakis, A. M., Haufe, F. L., Wolf, P., Masia, L., & Riener, R. (2021). Soft Robotic Suits: State of the Art, Core Technologies, and Open Challenges. *IEEE Transactions on Robotics.*, Nuckols, R. W., Takahashi, K. Z., Farris, D. J., Mizrachi, S., Riener, R., & Sawicki, G. S. (2020). Mechanics of walking and running up and downhill: A joint-level perspective to guide design of lower-limb exoskeletons. *PLoS one*, 15(8)., [3] Han, H., Wang, W., Zhang, F., Li, X., Chen, J., Han, J., & Zhang, J. (2021). Selection of Muscle-Activity-Based Cost Function in Human-in-the-Loop Optimization of Multi-Gait Ankle Exoskeleton Assistance. *IEEE Transactions on Neural Systems and Rehabil*

Human-in-the-Loop optimization for downhill walking with the Myosuit

Lukas Bergmann¹, Gleb Koginov², Steffen Leonhardt¹, Robert Riener², Michele Xiloyannis²

¹Medical Information Technology (MedIT), RWTH Aachen; ²Sensory Motor Systems (SMS) Lab, ETH Zurich;

1 Introduction

Recent developments in the field of lightweight wearable robots have brought such devices a step closer to being beneficial for both, people with gait impairments and those with physiological gait patterns [1]. With the wider adoption of this technology in everyday life, personalized timing and magnitude of assistance become crucial for support in unstructured environments.

2 Methods and Materials

- We applied a method to determine **individual assistance trajectories** for downhill walking based on human-in-the-loop optimization.
- The developed optimization procedure is tested using the **Myosuit** - a tendon-driven soft robot for mobility assistance. The Myosuit supports weight-bearing of the **hip and knee joint in the stance phase** by applying force through compliant tendons.
- We derived a model-based trajectory by utilizing the joint torques found by Nuckols et al in [2] and used it as a reference model. The model can be characterized by the **timing and magnitude of two peak values** (see reference profile in Fig. 2).
- Similar to [3], the **covariance matrix adaptation evolution strategy algorithm** (CMA-ES) and **spline interpolation** were applied to vary the parameter set and find assistance profiles **minimizing the muscle activity** (Fig. 1).
- The **cost function** to be minimized is based **on muscular effort**.

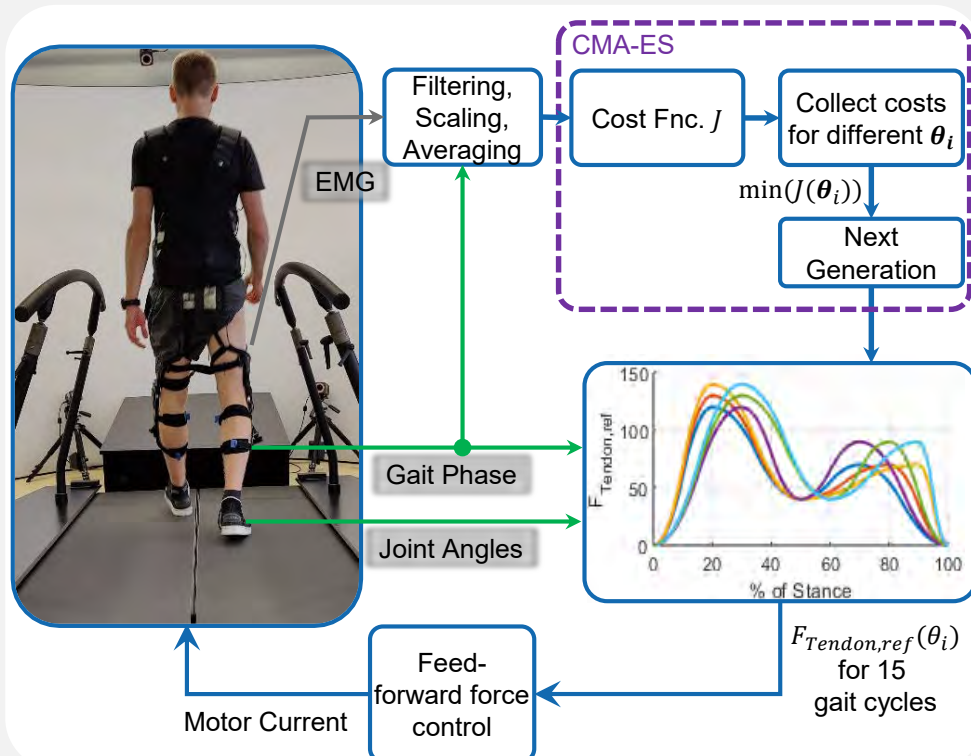


Fig. 1: Overall human-in-the-loop optimization concept with CMA-ES based on EMG cost function.

4 Results and Discussion

- We derived individual assistance trajectories for six healthy subjects at a descending slope of ten degrees.

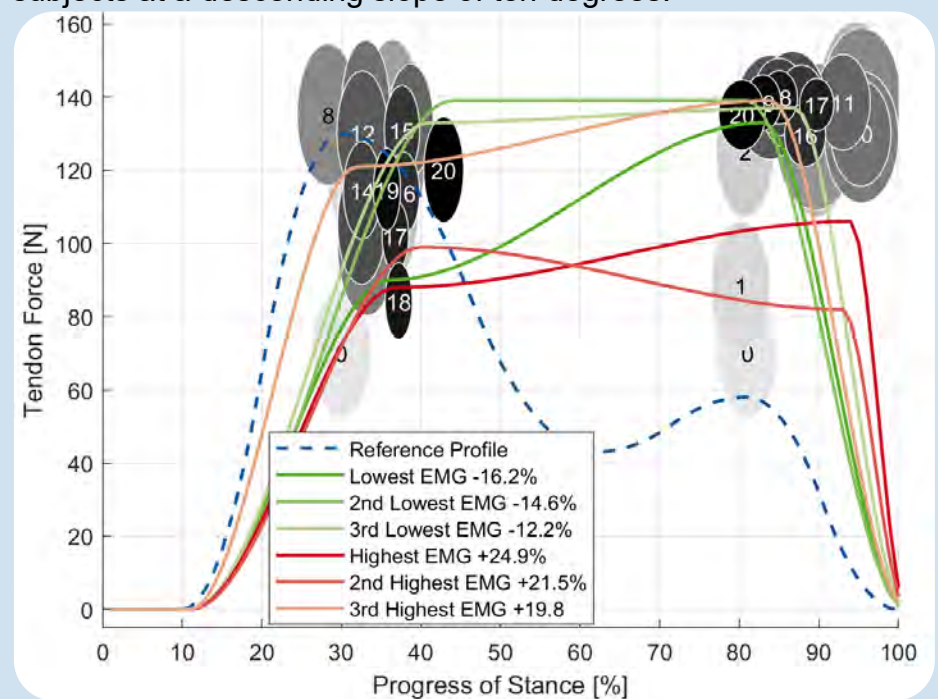


Fig. 2: Mean & Std.-Dev. of the CMA-ES algorithm (grey circles) & six example trajectories (green and red curves) for subject 5.

- Results have shown that a timely applied assistance force decreases muscle activity of knee extensors compared to the reference assistance trajectory in all subjects.

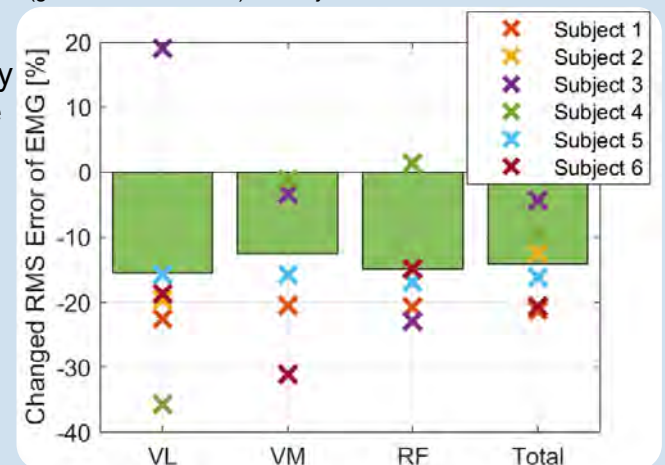


Fig. 3: Average change of the RMS error of EMG signals (Vastus Lateralis VL, Vastus Medialis VM, Rectus Femoris RF) compared to the reference trajectory.

5 Conclusion & Outlook

The individualized assistance shows promising results for reducing muscle activity during downhill walking. In the next step, we will further evaluate the optimized trajectories by comparing the subject's metabolic cost, muscle activity, and lower limb kinematics. Our long-term goal is to define a standardized method for determining optimal support for different slopes and gait patterns.

References

- Xiloyannis, M., Alicea, R., Georgarakis, A. M., Haufe, F. L., Wolf, P., Masia, L., & Riener, R. (2021). Soft Robotic Suits: State of the Art, Core Technologies, and Open Challenges. *IEEE Transactions on Robotics*.
- Nuckols, R. W., Takahashi, K. Z., Farris, D. J., Mizrahi, S., Riener, R., & Sawicki, G. S. (2020). Mechanics of walking and running up and downhill: A joint-level perspective to guide design of lower-limb exoskeletons. *PLoS one*, 15(8), e0231996.
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REHAB WEEK 2021

23-25 SEPTEMBER 2021
VIRTUAL EVENT



TOPIC: Wearable devices

P-142

Feasibility of Using Low-End Wearable Armbands and Unsupervised Transfer Learning for Seamless Myoelectric Control

Lai, Yuxiao 1; Elwin, Matthew L. 1; Dewald, Julius P.A. 1; Sohn, M. Hongchul 1
1: Northwestern University, Evanston, USA

Myoelectric control uses electromyography (EMG) signals as human-originated input to enable intuitive interfaces with machines. As such, recent rehabilitation robotics employs myoelectric control to autonomously classify user intent or operation mode using machine learning. However, performance in such applications inherently suffers from the non-stationarity of EMG signals across measurement conditions. Current laboratory-based solutions rely on careful, time-consuming control of the recordings or periodic recalibration, impeding real-world deployment. We propose that robust yet seamless myoelectric control can be achieved using a low-end, easy-to-“don” and “doff” wearable sensor combined with unsupervised transfer learning. Here, we test the feasibility of one such application using a consumer-grade sensor (Myo armband, 8 channels @ 200 Hz) for gesture classification across measurement conditions: 5 users x 10 days x 3 wearing locations (dataset from [1]). Specifically, we first train a deep neural network using Temporal-Spatial Descriptors (TSD) [2] with labeled source data from any particular user, day, or location. We then apply the Self-Calibrating Asynchronous Domain Adversarial Neural Network (SCADANN) [3], which automatically adjusts the trained TSD to improve classification performance for unlabeled target data from a different user, day, or location. Compared to the original TSD, SCADANN improves accuracy by $12 \pm 5.2\%$ (avg \pm sd), $9.6 \pm 5.0\%$, and $8.6 \pm 3.3\%$ across all possible user-to-user, day-to-day, and location-to-location cases, respectively. In one best-case scenario, accuracy improves by 26% (from 67% to 93%), whereas sometimes the gain is modest (e.g., from 76% to 78%). While elucidating the contexts in which SCADANN performs better/worse will be most informative for future development, we postulate that the proposed approach is feasible and promising and can be further tailored for seamless myoelectric control of powered prosthetics or exoskeletons.

References: S. Kanoga et al., “Are armband sEMG devices dense enough for long-term use?--Sensor placement shifts cause significant reduction in recognition accuracy”, Biomedical Signal Processing and Control, 2020., R.N. Khushaba, et al., “A Framework of Temporal-Spatial Descriptors-Based Feature Extraction for Improved Myoelectric Pattern Recognition”, IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2017., U. Cv̇te-Allard et al., “Unsupervised Domain Adversarial Self-Calibration for Electromyography-Based Gesture Recognition,” IEEE Access, 2020.

This work was supported by: Northwestern Robotics program

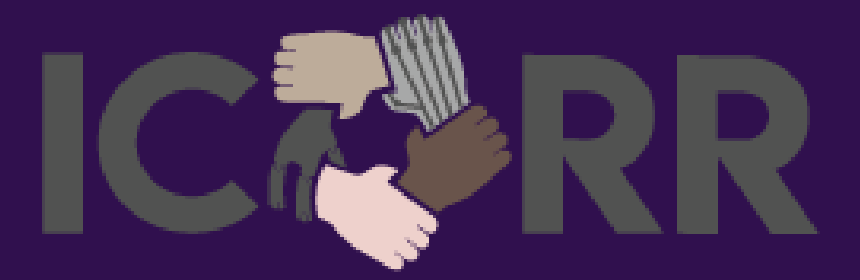
Feasibility of Using Low-End Wearable Armbands and Unsupervised Transfer Learning for Seamless Myoelectric Control

Sonia Yuxiao Lai¹, Matthew L. Elwin^{1,2}, Julius P.A. Dewald^{3,4}, M. Hongchul Sohn³



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¹Master of Science in Robotics Program; ²Department of Mechanical Engineering;
³Physical Therapy and Human Movement Sciences; ⁴Biomedical Engineering, Northwestern University



HIGHLIGHTS:

1. Robust performance and seamless usability are crucial for intuitive HMI with myoelectric control.

2. We tested feasibility of using a low-end wearable sensor combined with unsupervised transfer learning.

3. Proposed approach improves accuracy across various measurement conditions without recalibration.

4. This framework is feasible and promising for seamless myoelectric control in rehabilitation robotics.

INTRODUCTION

Myoelectric control uses electromyography (EMG) signals as human-originated input to enable intuitive interfaces with machines.

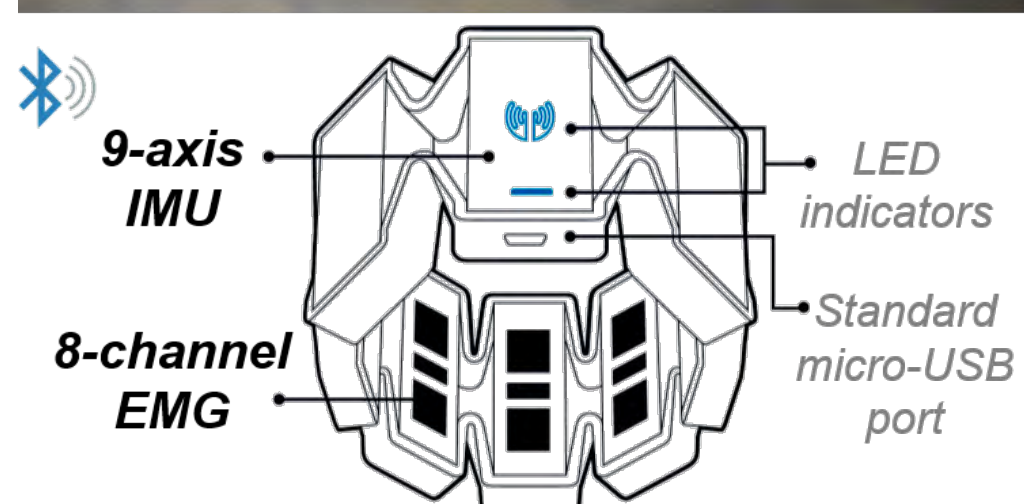
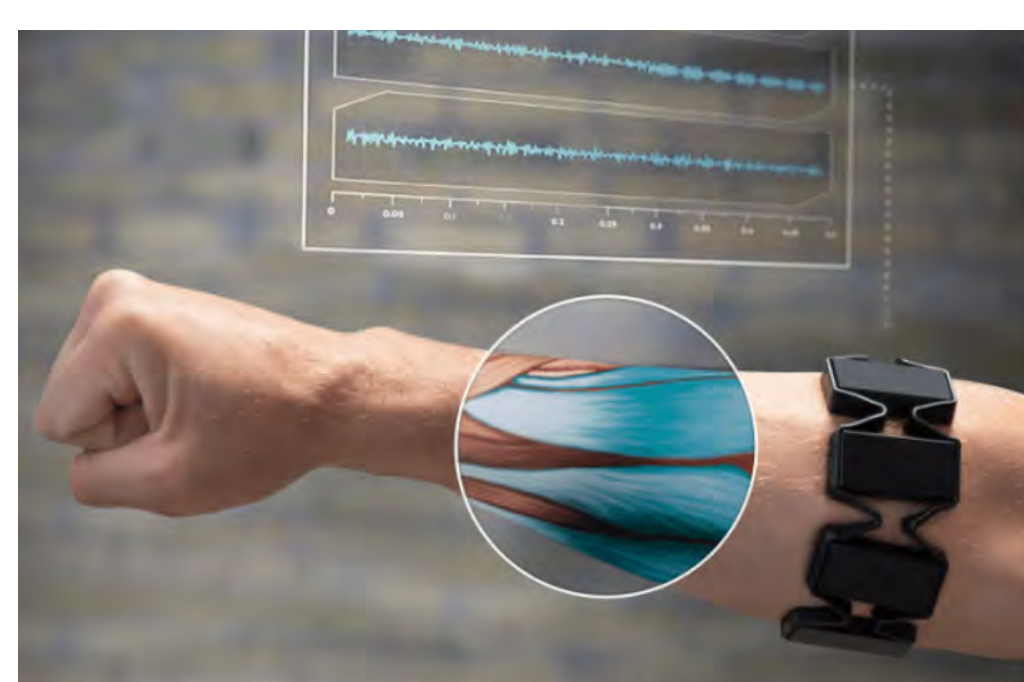
- Recent rehabilitation robotics employs myoelectric control to autonomously classify user intent or operation mode using machine learning.
- However, performance in such applications inherently suffers from the non-stationarity of EMG signals across measurement conditions. Current laboratory-based solutions rely on *careful, time-consuming control of the recordings or periodic recalibration*, impeding real-world deployment [1].

We propose that robust yet seamless myoelectric control can be achieved using a low-end, easy-to-“don” and “doff” wearable sensor combined with unsupervised transfer learning.

APPROACH

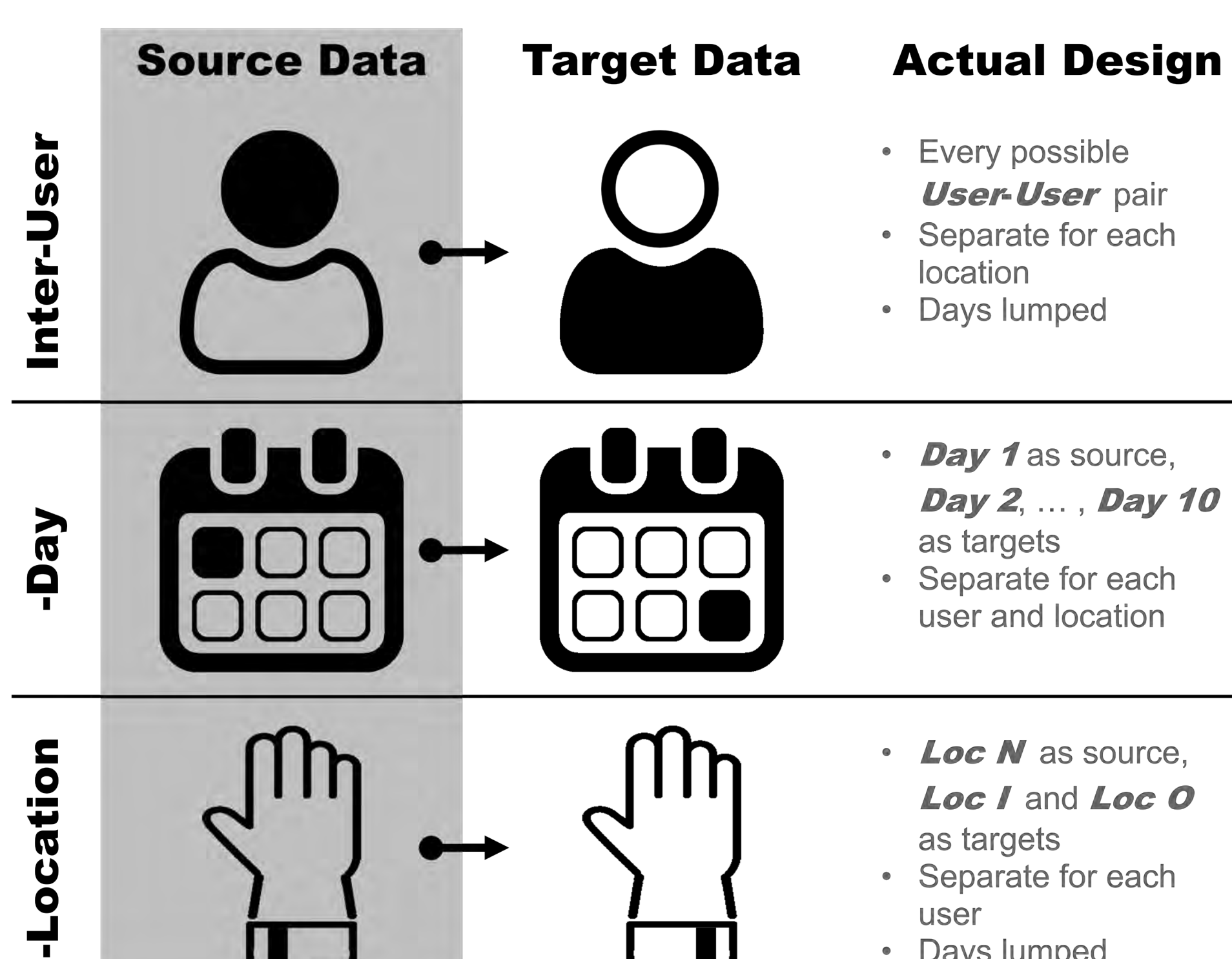
Here, we tested the feasibility of one such application using a consumer-grade armband sensor for robust gesture classification across various measurement conditions.

- Device:
Myo armband,
8 EMG channels @ 200 Hz
- Dataset (from [2]):
5 users x 10 days x
3 wearing locations
(Neutral, Inward- and
Outward rotated)
- Gestures:
22 wrist and hand gestures
(8 1-DoF and 14 2-DoF) [3]



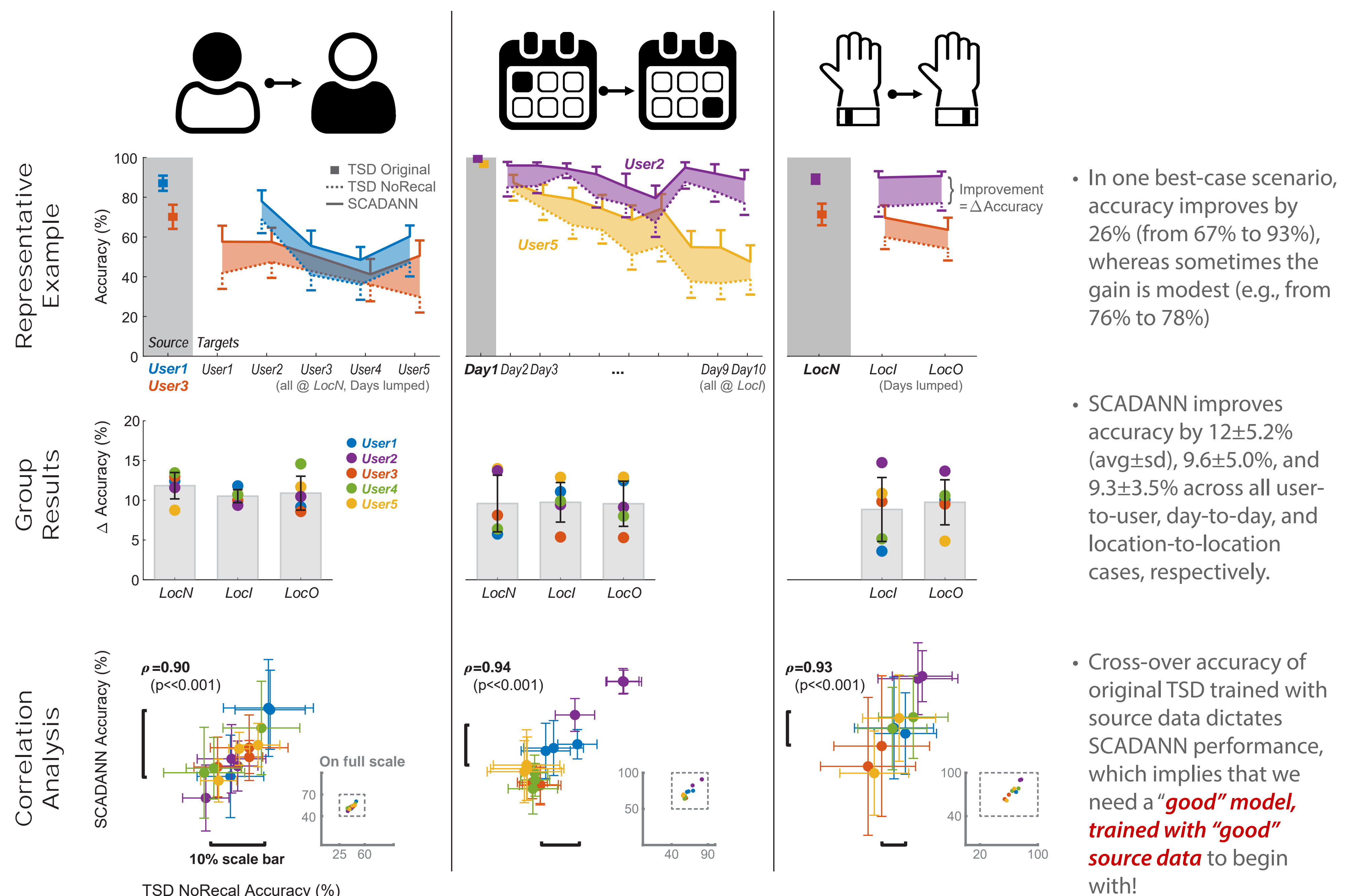
We adopted an unsupervised domain adversarial self-calibration algorithm for transfer learning.

- Train a deep neural network using Temporal-Spatial Descriptors (TSD) [4] with labeled **Source Data** from any particular user, day, or location.
- Self-Calibrating Asynchronous Domain Adversarial Neural Network (SCADANN) [5] automatically adjusts the trained TSD to improve classification performance for unlabeled **Target Data** from a different user, day, or location.

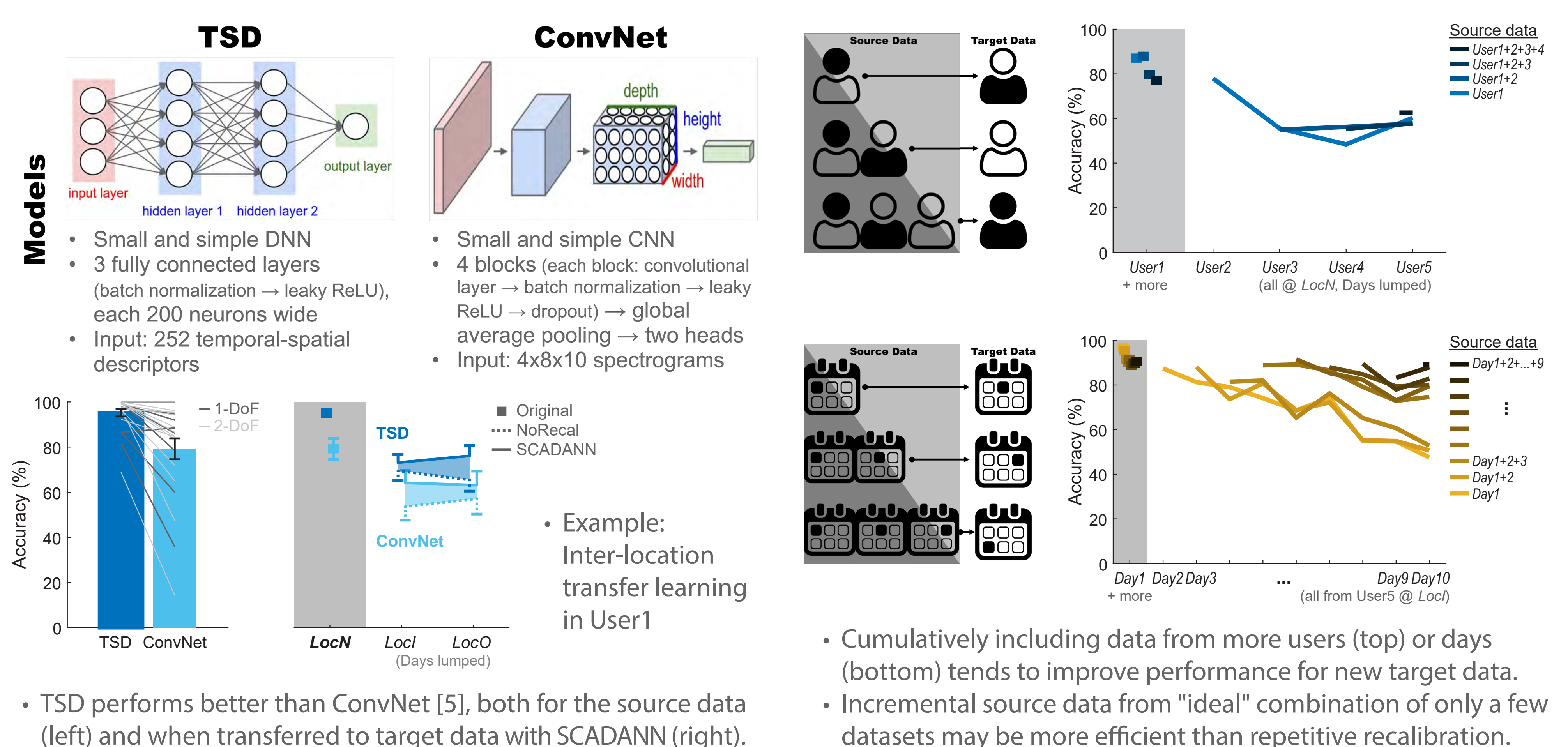


RESULTS

1. Transfer learning (e.g., SCADANN) can improve accuracy across various measurement conditions (inter-user, -day, -location), without the need to recalibrate.



2. A) Better selection of initial model (e.g., TSD vs ConvNet) and B) Training that model with incremental source data can improve performance of transfer learning (e.g., SCADANN).



CONCLUSIONS

The proposed approach is feasible and can be further tailored.

- Comparable (or better) performance (i.e., improvement in accuracy) to similar approaches [5-7], even with no parameter optimization and a limited data set
- More rigorous validation: Training, calibration, validation, testing
- Combined effects of transfer learning across contexts (e.g., user x day)

The proposed approach is promising for seamless myoelectric control of powered prosthetics or exoskeletons.

References

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- Kanoga et al., 2020, Biomed Sig Process & Control
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- Khushaba, et al., 2017, IEEE TNSRE
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Funding support

This project is supported by the Northwestern Robotics program.

REHAB WEEK 2021

23-25 SEPTEMBER 2021
VIRTUAL EVENT



TOPIC: Wearable devices

P-143

Survey-based Identification of Design Requirements and Constraints for a Wearable Tremor Suppression Device

Zhou, Yue 1; Box, Devin 1; Hardy, Kenneth 1; Jenkins, Mary E. 1; Garland, S. Jayne 1; Naish, Michael 1; Trejos, Ana Luisa 1

1: The University of Western Ontario, London, Ontario, Canada

Parkinsonian tremor has severely impacted the lives of 65% of individuals with Parkinson's disease, and nearly 25% do not respond to traditional treatments. Although wearable tremor suppression devices (WTSDs) have become a promising alternative approach, only a few of them have become commercially available. The WTSD technology is still in the early stages of development, and no studies have reported the stakeholders' opinions on this technology and their desired design requirements. To address this issue, this study presents the findings from an online survey that was distributed to affected Canadians and Canadian movement disorder specialists (MDS). A total of 101 affected individuals and 24 MDS completed the survey. Participants provided information on demographics, the current state of treatments, opinions on the WTSDs, and the desired design requirements of future WTSDs. It was found that both groups of participants are generally open to using WTSDs to manage tremor. In addition, people who are not satisfied with their current treatment are more enthusiastic about this technology. The most important design requirement to end users is the adaptability to lifestyle, followed by weight and size, accurate motion, comfort, safety, quick response, and cost. Lastly, most of the participants (65%) think that the device should cost under \$500. The findings from this study can be used as guidelines for the development of future WTSDs and the optimization of existing WTSDs, such that the future generations could be evaluated and accepted by the end users.

References: R. J. Elble, "Tremor," in *Neuro-Geriatrics*. Springer, 2017, pp. 311-326., Y. Zhou et al., "Design and preliminary performance assessment of a wearable tremor suppression glove," *IEEE Transactions on Biomedical Engineering*, doi: 10.1109/TBME.2021.3080622, T. F. Burgess, "A general introduction to the design of questionnaires for survey research," Leeds: University of Leeds, 2001.

This work was supported by: Natural Sciences and Engineering Research Council, Canadian Institutes of Health Research, Canadian Foundation for Innovation, Ontario Research Fund, Ontario Ministry of Economic Development, Trade and Employment and the Ontario Ministry of Research and Innovation through the Early Researcher Award, Peter C. Maurice Research Fellowship in Biomedical Engineering



Y. Zhou¹, D. Box², K.G. Hardy³, M.E. Jenkins⁴, S.J. Garland⁵, M.D. Naish^{1,6,7} and A.L. Trejos^{1,7}

¹School of Biomedical Engineering, ²School of Kinesiology, ³Ivey Business School, ⁴Movement Disorders Program, Clinical Neurological Sciences, ⁵Faculty of Health Sciences, ⁶Department of Mechanical and Materials Engineering, ⁷Department of Electrical and Computer Engineering, Faculty of Engineering, Western University, London, Ontario, Canada

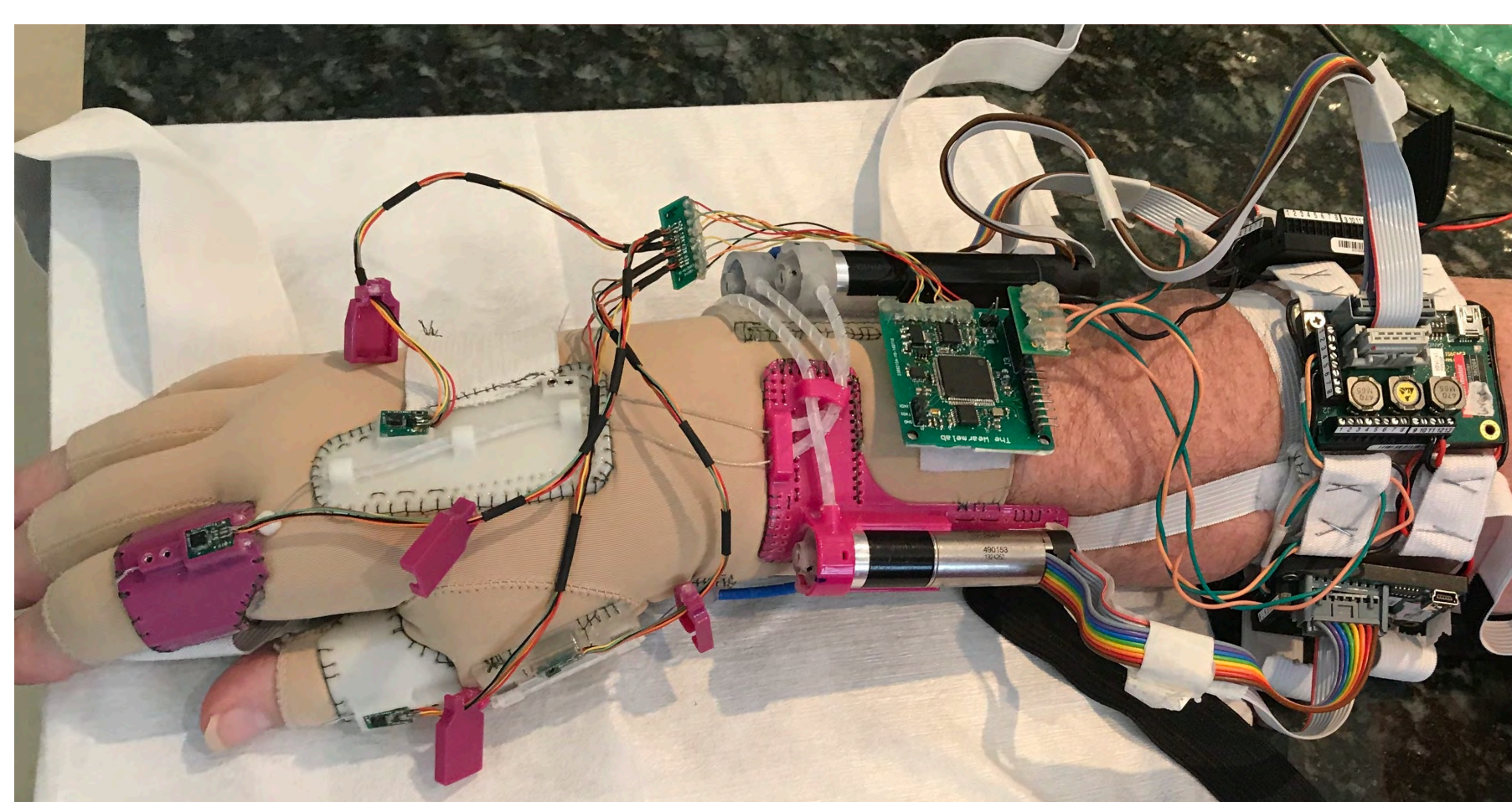
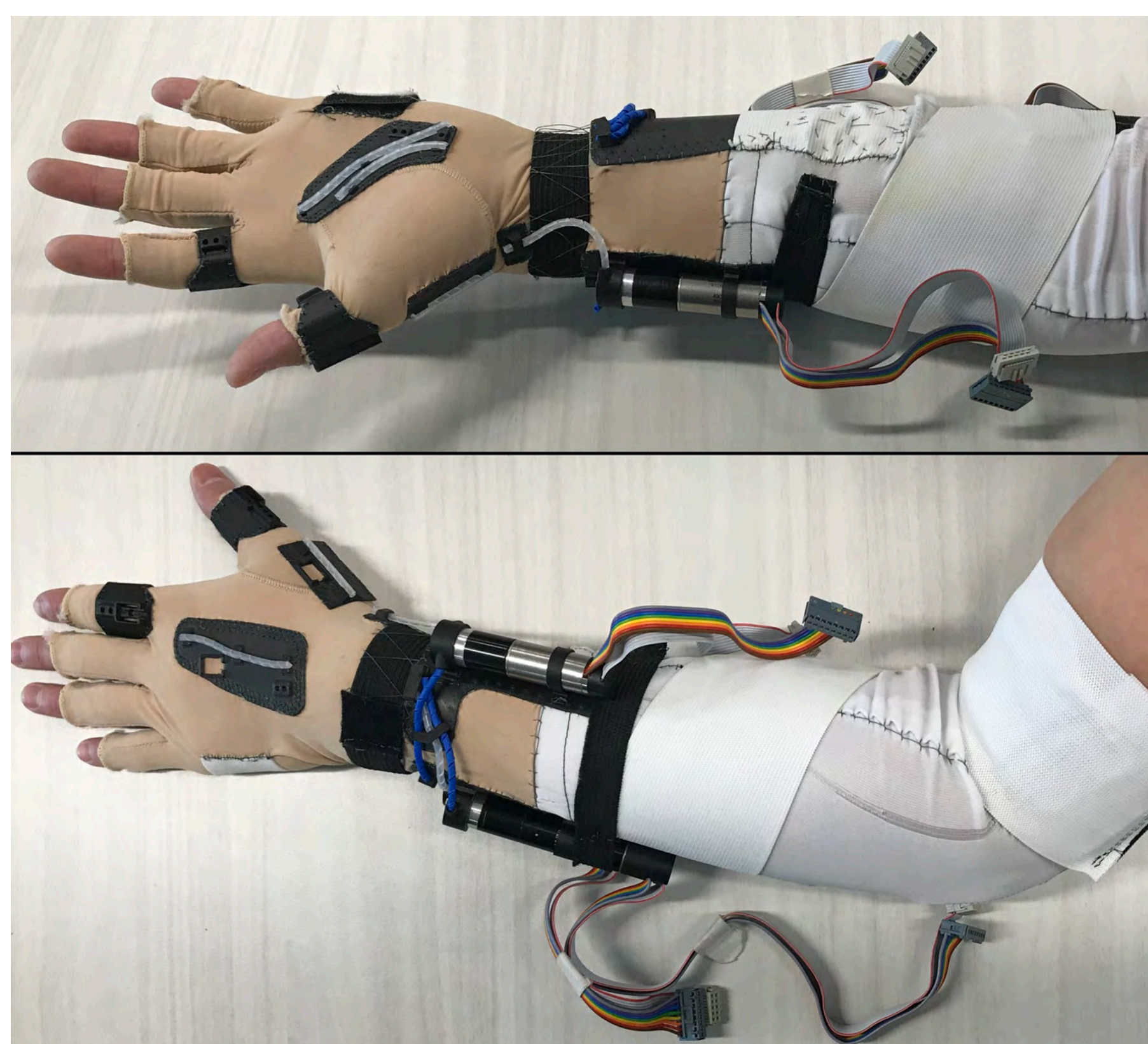
Background

Tremor is one of the most disabling symptoms of Parkinson's disease (PD). Medication and brain surgery are the mainstays of treatment for parkinsonian tremor; however, they are often associated side effects and complications.



As an alternative, research in wearable tremor suppression devices (WTSD) has been facilitated by the development of wearable technology. Although WTSDs have shown promising results in tremor suppression, none of these WTSDs have become commercially available.

The lack of acceptance by the stakeholders may be caused by several factors, such as size, weight, discomfort, safety, cost, performance when suppressing tremor, adaptability to the user's lifestyle, or inadequate knowledge of this technology among the stakeholders.



Y. Zhou, *et al.*, "Design and Preliminary Performance Assessment of a Wearable Tremor Suppression Glove," IEEE Transactions on Biomedical Engineering, vol. 68, no. 9, pp. 2846–2857.

Objectives

In order to facilitate the acceptance of WTSDs by clinicians and individuals living with PD, it is imperative to understand why the current WTSDs are not widely used, and what aspects of a WTSD are considered to be the most important to the stakeholders.

Survey Design

Two separate online surveys:

	Open-ended Questions	Multiple Choice
Individuals with PD	1	16
Movement disorder specialists	2	11

- Demographic information (including age, sex, years since PD diagnosis), treatments received, and their opinions on the treatments and WTSDs.
- Information about their experience when treating parkinsonian tremor and their opinions on the use of a WTSD.

Both groups were asked to rank the aspects of a WTSD that they consider important.

Participant Recruitment

Participants with PD were contacted through Parkinson's societies and communities within Canada.

Movement disorder specialists (MDS) were identified through the Canadian Movement Disorder Group.

The participants agreed to give consent to enroll by completing the questionnaire.

- 110 individuals living with PD
 - 101 completed, 9 withdrew
- 61 movement disorder specialists
 - 25 responded, of which 24 completed

Data Analysis

Cross-tabulation analysis was used to examine potential associations between the following independent variables and response variables:

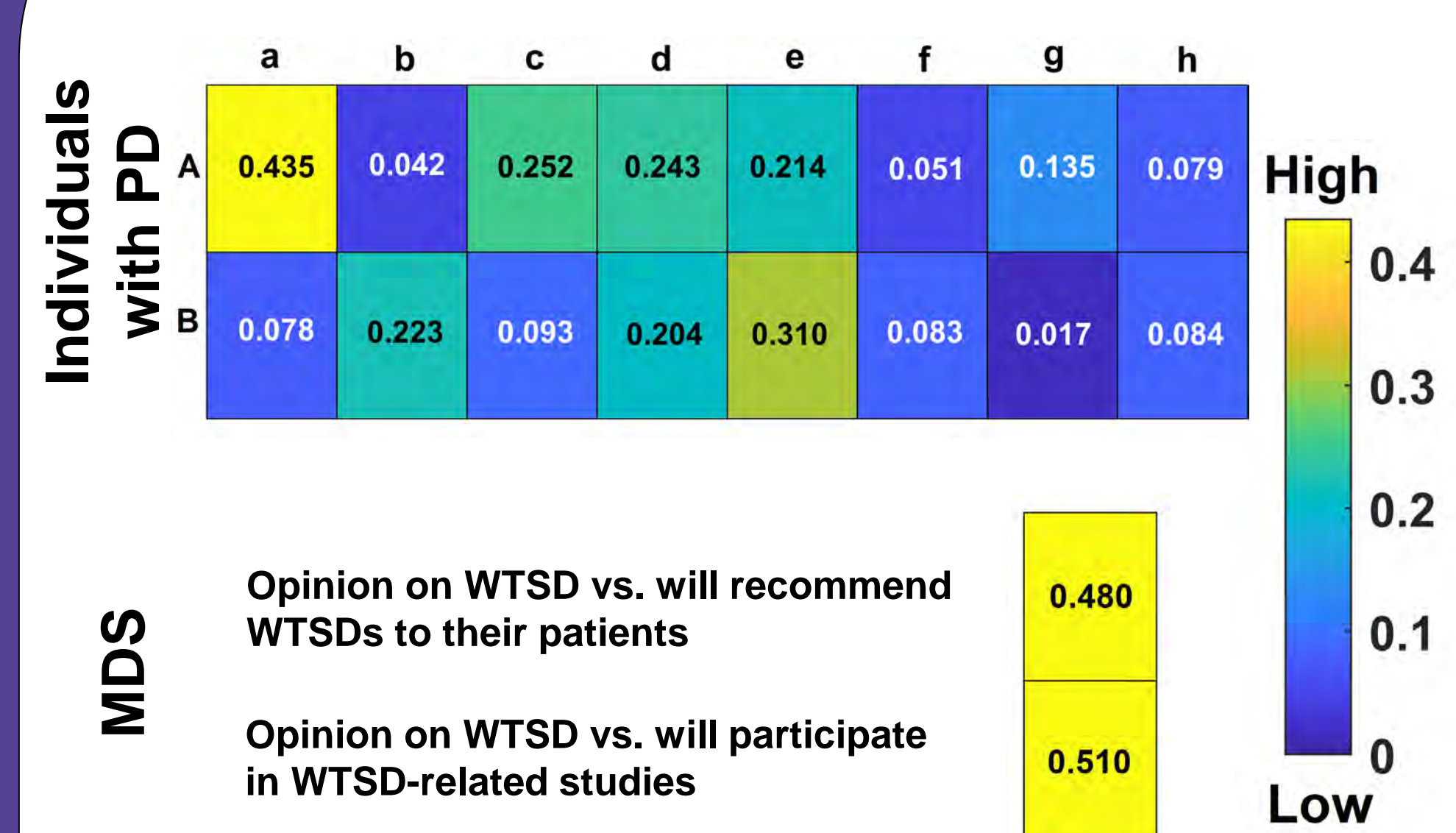
Groups	Independent Variables	Response Variables
Individuals with PD	Age (a)	1. Opinion on the concept of a WTSD (A) 2. Opinion on trying a WTSD (B)
	Sex (b)	
	Awareness of WTSDs (c)	
	Overall satisfaction of the treatment they currently receive (d)	
	Efficiency of their current treatment on managing tremor (e)	
	Difficulty of managing treatment in daily life (f)	
	Side effects of their current treatment (g)	
	Cost of their current treatment (h)	
MDS	Opinion on WTSDs	1. Whether they will recommend WTSDs to their patients 2. Whether they will participate in WTSD-related studies

* Note that the bolded letters are used to indicate the statistical associations in the Results section.

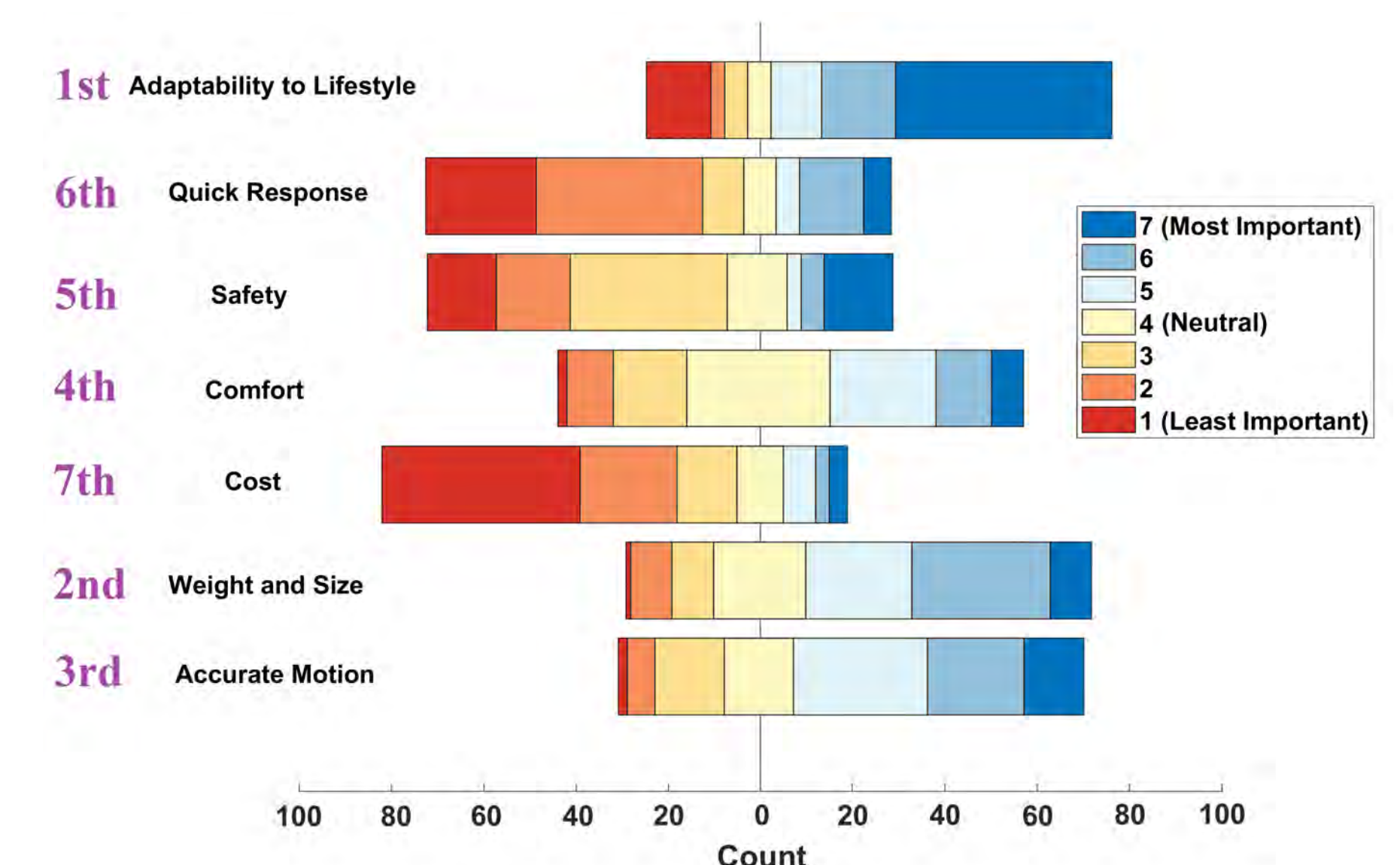
Adaptability to lifestyle, quick response, safety, comfort, cost, weight and size, and accurate motion were ranked by both groups to acquire design requirements for future WTSDs.

Results

Statistical Association:

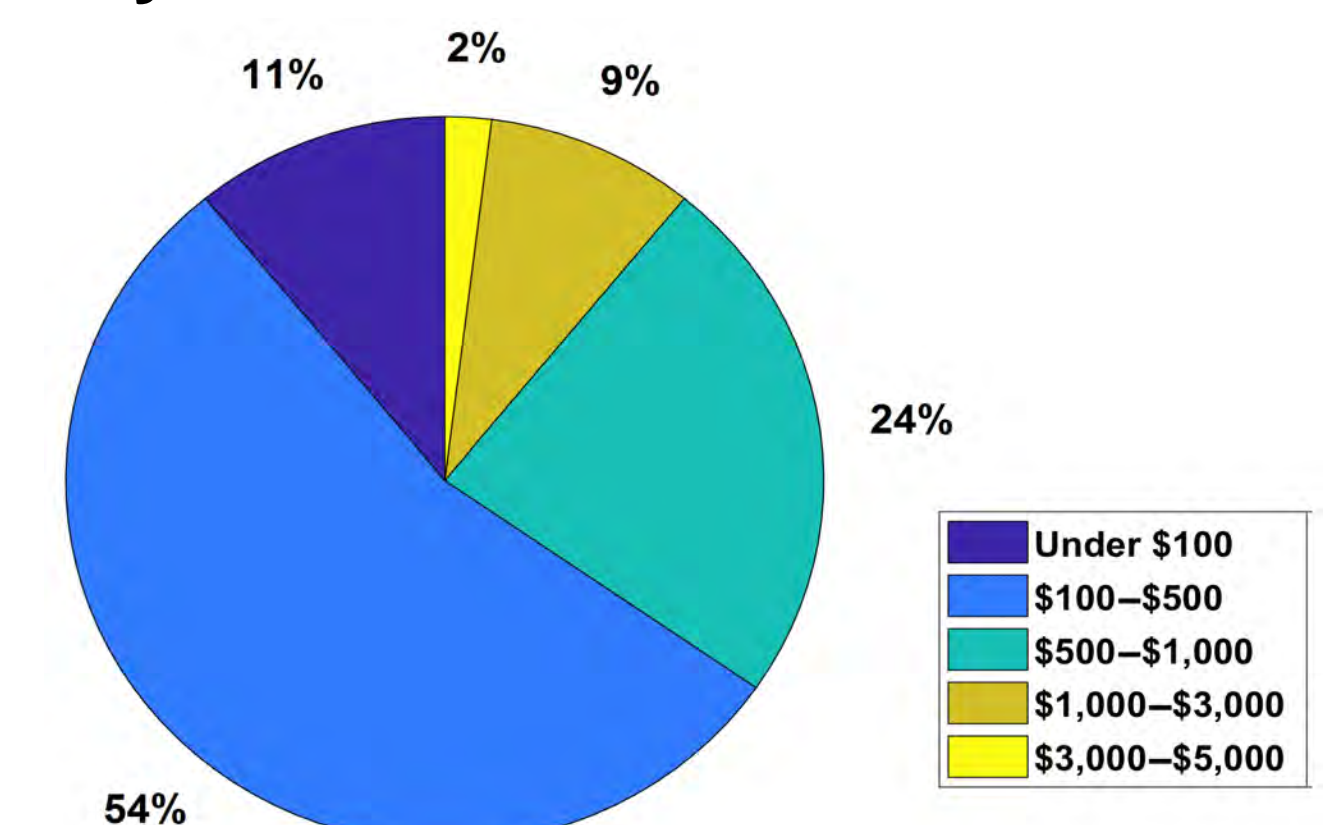


Design Requirements (individuals with PD):



No agreement was obtained from the MDS on the design requirements of future WTSDs.

Affordability: Individual with PD



Conclusions

- Both groups of participants are generally open to the idea of using WTSDs for managing tremor; however, many respondents require more evidence of the successful implementation of WTSDs.
- The information collected on the design requirements can be used as guidelines for the development of future WTSDs and optimization of existing WTSDs.

Acknowledgements

This research was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada and the Canadian Institutes of Health Research (CIHR) through a Collaborative Health Research Projects (CHRP) grant #396234; by the Canadian Foundation for Innovation (CFI), by the Ontario Research Fund (ORF); by the Ontario Ministry of Economic Development, Trade and Employment and the Ontario Ministry of Research and Innovation through the Early Researcher Award; and by the Peter C. Maurice Research Fellowship in Biomedical Engineering.

REHAB WEEK 2021

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VIRTUAL EVENT



rehabweek
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TOPIC: Human-machine interfaces in rehabilitation

P-144

Joint Action is a Framework for Understanding Partnerships Between Humans and Upper Limb Prostheses

Dawson, Michael R. 1; Parker, Adam S. R. 1; Williams, Heather E. 1; Shehata, Ahmed W. 1; Hebert, Jacqueline S. 1; Chapman, Craig S. 1; Pilarski, Patrick M. 1
1: University of Alberta, Edmonton, Canada

Recent advances in upper limb prostheses have led to significant improvements in hardware design, allowing users to perform more movements. However, the method for controlling them via user-generated signals remains challenging. To address this issue, various machine learning controllers have been developed to better predict the intent of the person with amputation and help them control their prosthesis. As these controllers become more intelligent and take on more autonomy in the system, the traditional approach of representing the human-machine interface as a human agent controlling a tool becomes limiting. One possible approach to improve the understanding and effectiveness of these interfaces is to model them as collaborative, multi-agent systems through the lens of joint action. The field of joint action has been commonly applied to two human agents who are trying to work jointly together to achieve a task, such as singing or dancing together. Using a joint action framework provides several benefits, including mechanisms for understanding how each agent represents the other's goal, the monitoring and prediction of each other's actions, the communication between agents, and their ability to adapt to each other. In this work, using the hallmarks of joint action [1], we compared three different prosthesis controllers, including conventional myoelectric control, pattern recognition [2], and adaptive switching [3]. The results of the comparison lead to a new perspective for understanding how existing myoelectric systems relate to each other, along with recommendations for how to improve these systems by increasing the collaborative communication between each agent. These recommendations provide a roadmap for future exploration, which can help guide the field towards unlocking the next level of performance for human-prosthesis interaction.

References: [1] C. Vesper, S. Butterfill, G. Knoblich, and N. Sebanz, "A minimal architecture for joint action," *Neural networks*, vol. 23, issues 8-9, Oct. 2010., [2] E. Scheme, and K. Englehart, "Electromyogram pattern recognition for control of powered upper-limb prostheses: State of the art and challenges for clinical use," *Journal of Rehabilitation Research & Development*, vol. 48, no. 6, pp. 643-660, Sept. 2011., [3] A. L. Edwards, M. R. Dawson, J. S. Hebert, C. Sherstan, R. S. Sutton, K. M. Chan, and P. M. Pilarski, "Application of Real-time Machine Learning to Myoelectric Prosthesis Control: A Case Series in Adaptive Switching," *Prosthetics & Orthotics Inter*

This work was supported by: Alberta Machine Intelligence Institute

REHAB WEEK 2021

23-25 SEPTEMBER 2021
VIRTUAL EVENT



TOPIC: Wearable devices

P-145

Comprehensive Kinematic Model of a Tendon-Driven Wearable Tremor Suppression Device

Daemi, Parisa 1; Zhou, Yue 1; Naish, Michael D. 1; Price, Aaron 1; Trejos, Ana Luisa 1.

1: Western University, London, Canada.

The limited space surrounding the human hand and the balance between positioning accuracy, compactness, and weight have been shown to be the main challenges in the design of wearable devices for the hand. For those experiencing hand tremor, wearable devices have been proposed to suppress or reduce tremor motion associated with neurological disorders. While they show promise, these devices need improvements in their design and control. Tendon-driven transmission systems have been proposed as a way to decrease the size and weight of these devices; however, they have complex control system requirements due to their substantially nonlinear behavior. To address this issue, this study focused on the development of a comprehensive kinematic model of a wearable tremor suppression glove that considers the configuration of its tendons and sheaths to calculate the tendon displacement during hand motion. This novel method quantifies a threshold bending angle for each joint, where the driven tendon touches the arc of the joint, by considering the bone geometry of the joint and the characteristics of the glove design. The derived kinematic model of the glove was verified by both simulation and benchtop experiments, and the new model has been validated during a single-joint movement showing a mean Pearson correlation coefficient for the kinematic model of 0.90 ± 0.01 . Furthermore, to demonstrate the accuracy of the proposed method, the experimental results were compared to the results of the new model and a model presented in [1]. The experimental results were a better match to the results of the new model, especially when the tendon displacement increases. The correlation coefficient was 4% higher with the new model. Therefore, the results show that the proposed model will support the design of tendon-driven exoskeleton devices to avoid slack and guide the optimal placement of tendons and sheaths.

References: D. Popov, I. Gaponov, and J. H. Ryu, "Portable exoskeleton glove with soft structure for hand assistance in activities of daily living," IEEE/ASME Transactions on Mechatronics, vol. 22, no. 2, pp. 865-875, 2017., ,

This work was supported by: The Natural Sciences and Engineering Research Council (NSERC) of Canada, The Canadian Institutes of Health Research (CIHR) through a Collaborative Health Research Projects (CHRP), The Canadian Foundation for Innovation (CFI), The Ontario Research Fund (ORF), The Ontario Ministry of Economic Development, Trade and Employment and the Ontario Ministry of Research and Innovation through the Early Researcher Award, The Peter C. Maurice Research Fellowship in Biomedical Engineering, A Transdisciplinary Bone & Joint Training Award.

Introduction

- Wearable tremor suppression devices have been proposed as a promising alternative to suppress or reduce tremor motion associated with neurological disorders.
- The limited working space of the human hand, the balance between positioning accuracy, compactness and weight have been introduced as the main challenges to design wearable hand devices.
- Although tendon-driven transmission systems have provided an alternative to decreasing the size and weight of these devices, they have complex control system requirements due to their substantially nonlinear behavior.

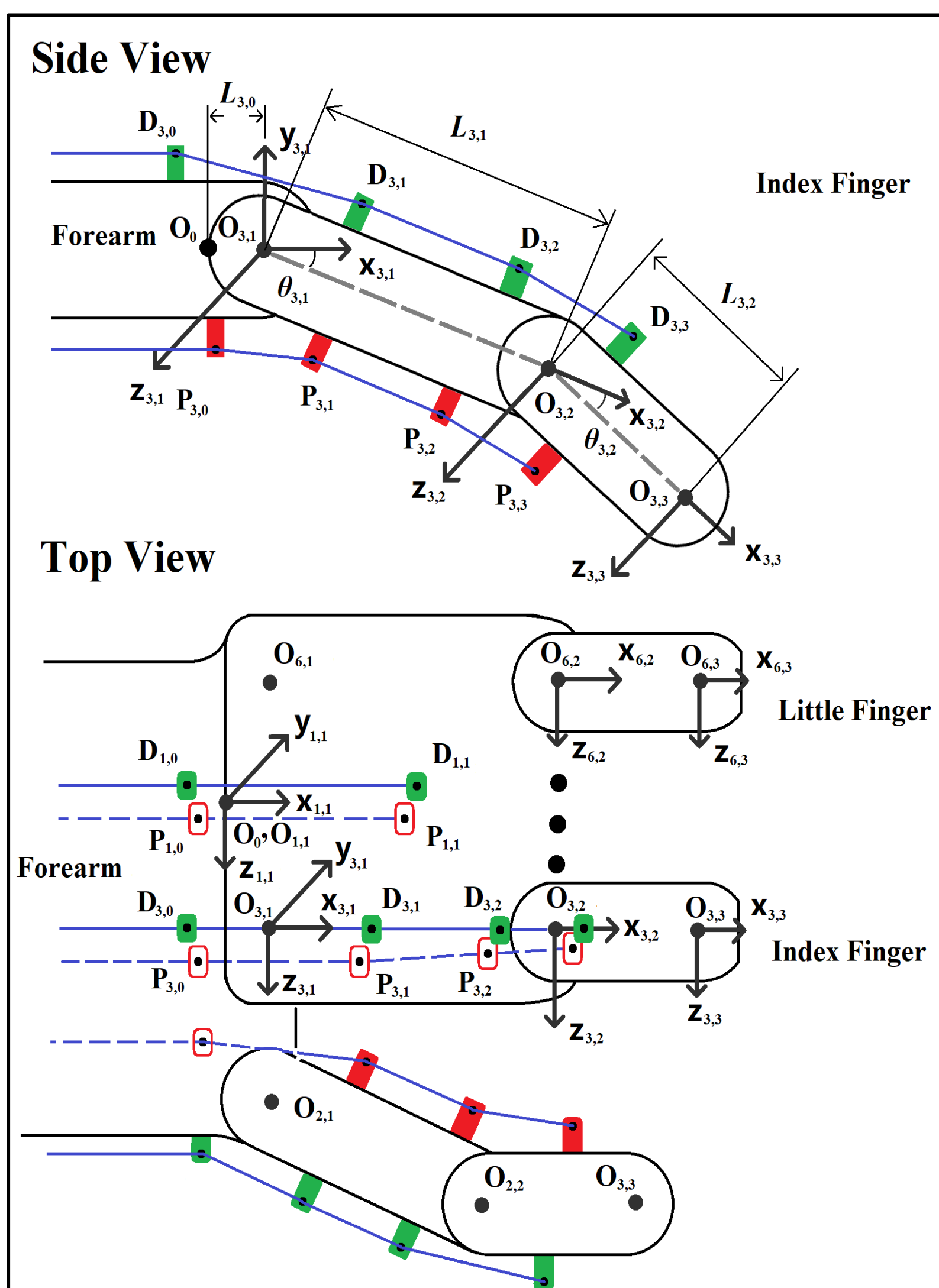


Objectives

- Develop a comprehensive kinematic model of a wearable tremor suppression device (WTSD) by considering the configuration of its tendons and sheaths.
- Propose a novel model to calculate the tendon displacement during hand motion in order to improve the tendon arrangement, study the kinetic model of the glove, and increase the accuracy of the control system.

Kinematic Model of the WTSD [*]

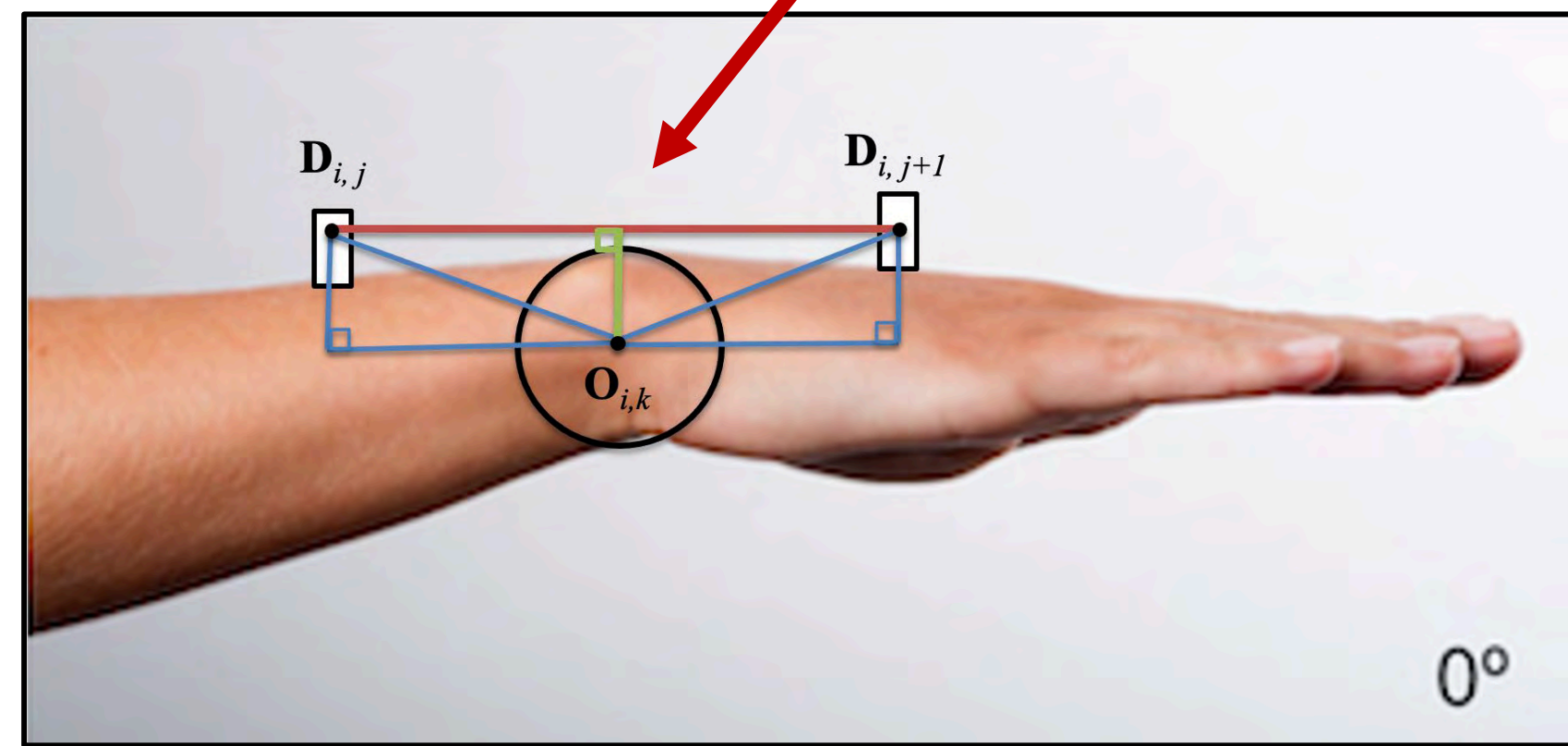
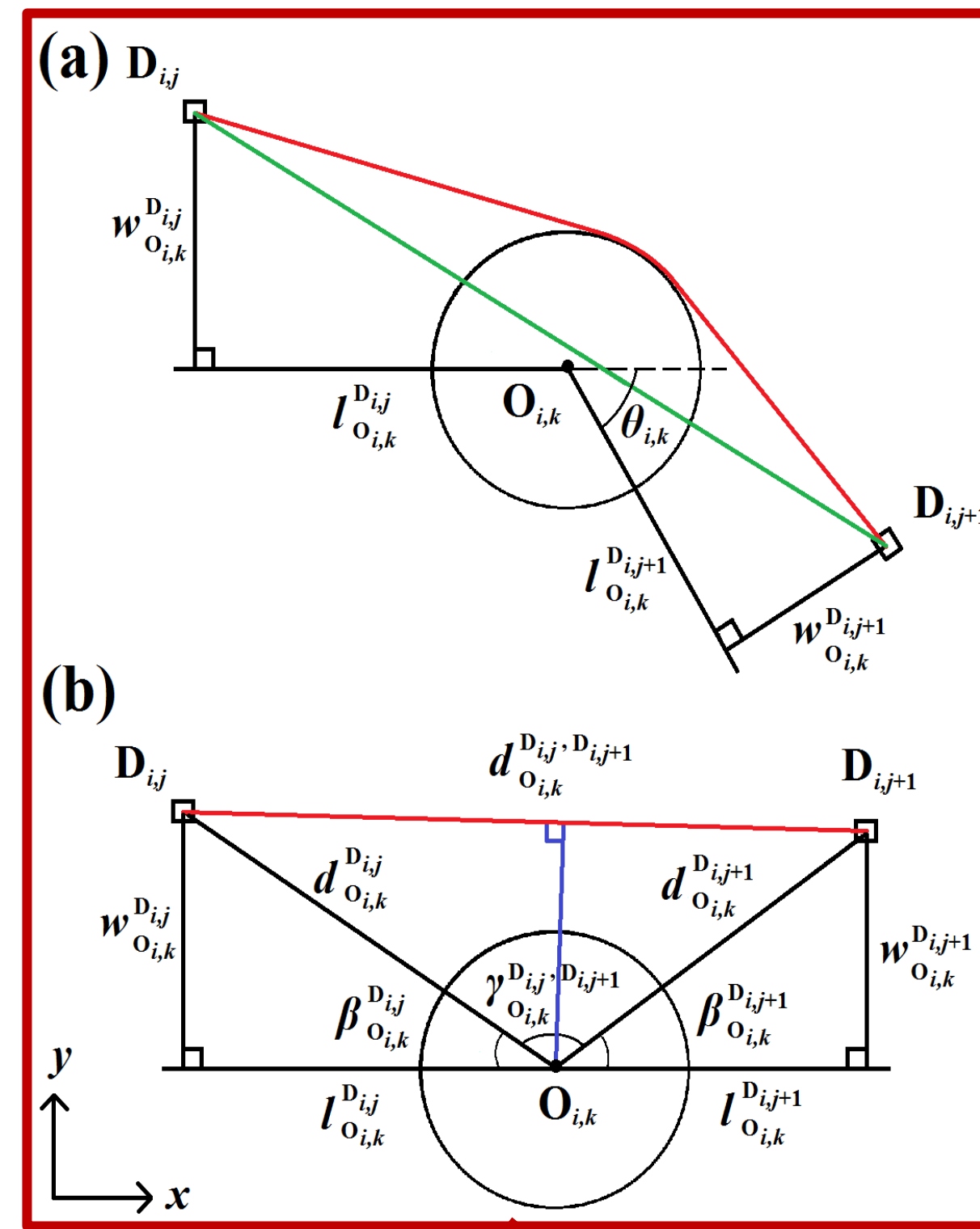
A schematic diagram of the hand for kinematic evaluation showing the guides placed on the dorsal and palmar sides of the hand.



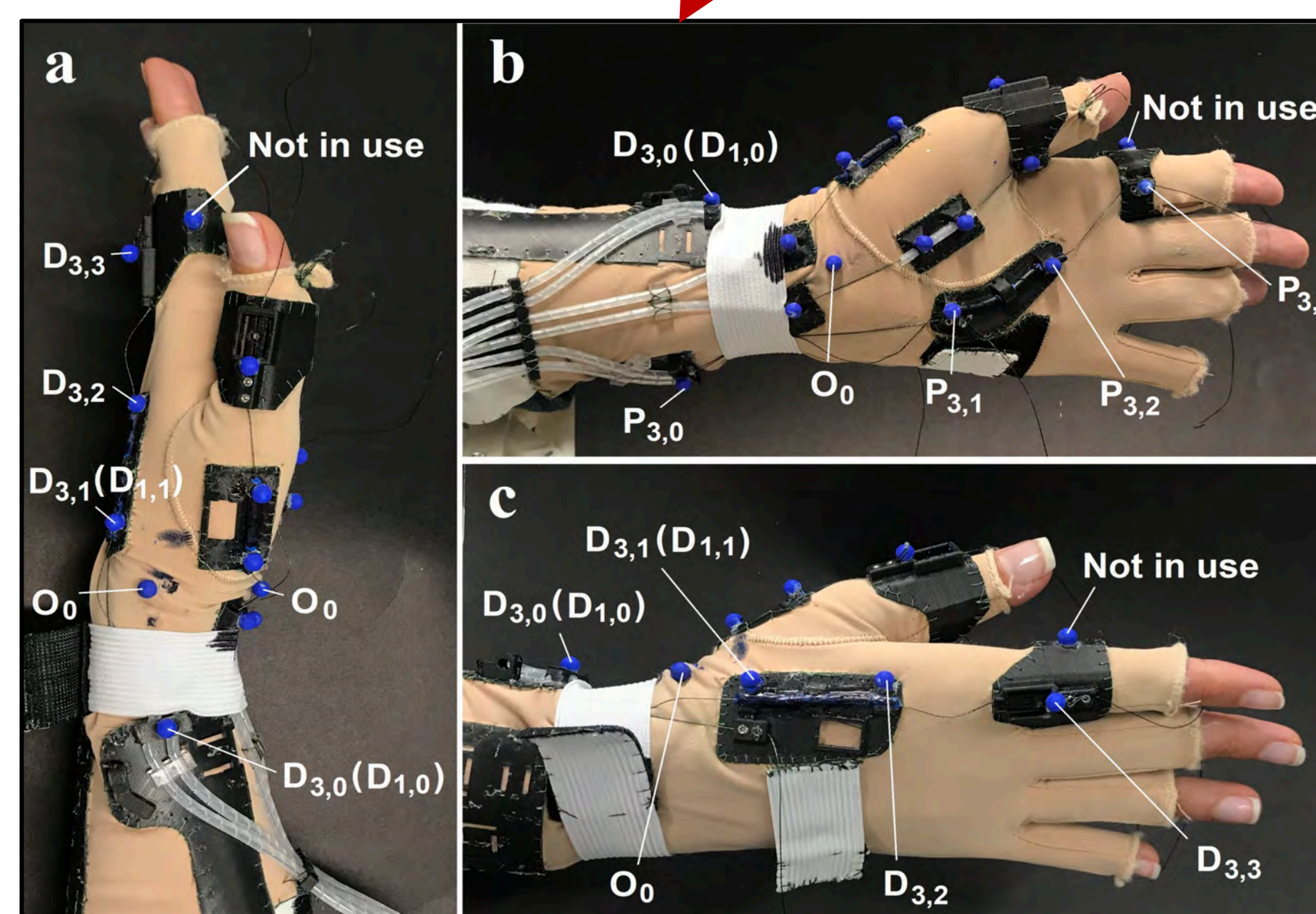
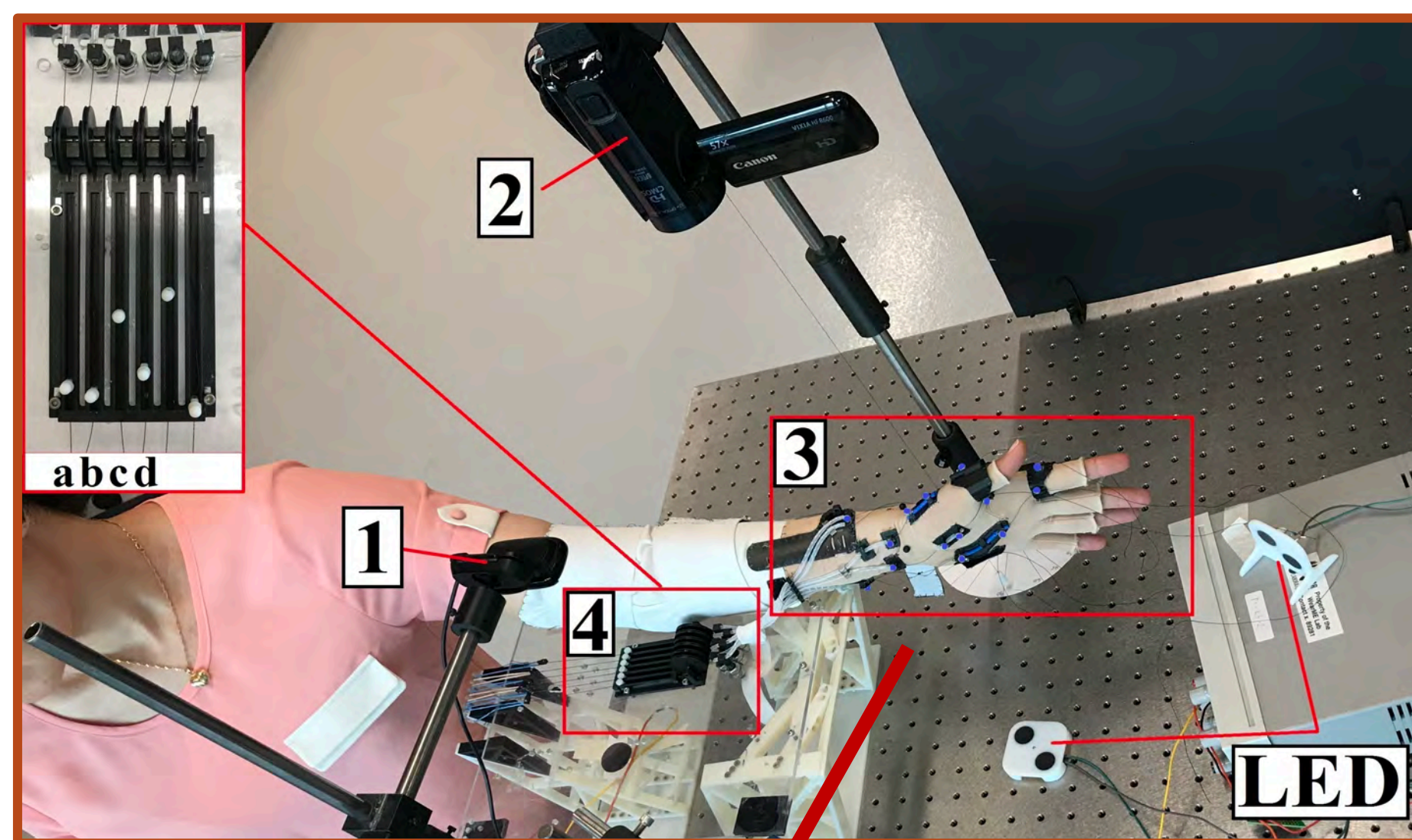
* P. Daemi, Y. Zhou, K. Inzunza, *et al.*, "Kinematic modeling and characterization of a wearable tremor suppression device for pathological tremor reduction," in *IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechanics (BioRob)*, New York, USA, November 29–December 3, 2020, pp. 1236–1241.

Mathematical Model

- These steps were followed in order to calculate the flexion–extension threshold angles of each joint:
 - Represent each joint as a circle with a radius r .
 - Compute the distance from the center of each joint to the adjacent guides.
 - Determine the β angles.
 - Calculate the height of the triangle $\Delta D_{i,j} O_{i,k} D_{i,j+1}$.
 - Find the bending angle of the joint (the threshold angle) and its corresponding index.
 - Calculate tendon length between two sequential dorsal guides on each side of the joint ($X_{D_{i,j}, D_{i,j+1}}$).

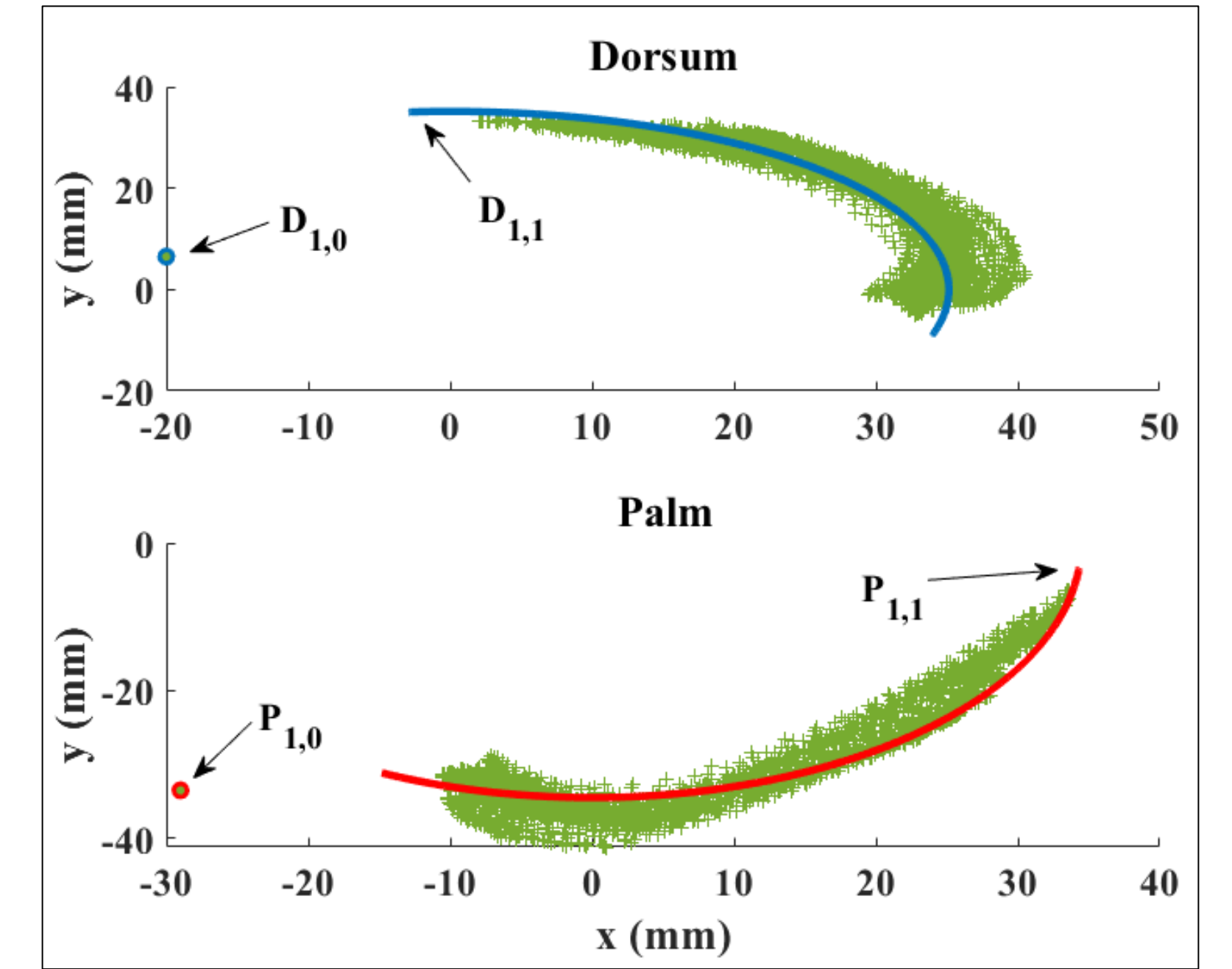


Evaluation

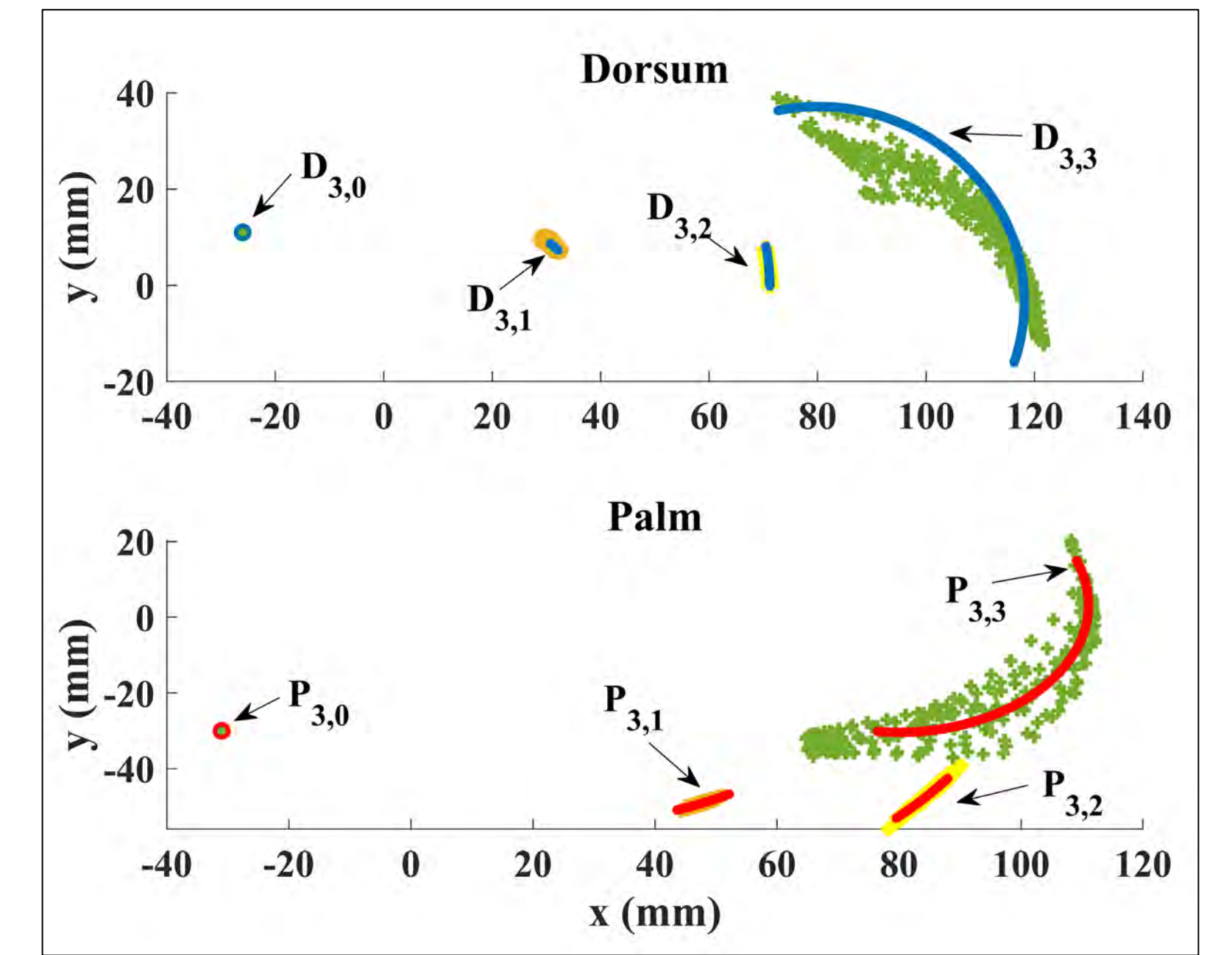


Results

- The **positions** of the guides at the **wrist joint** in the plane of flexion–extension motion.

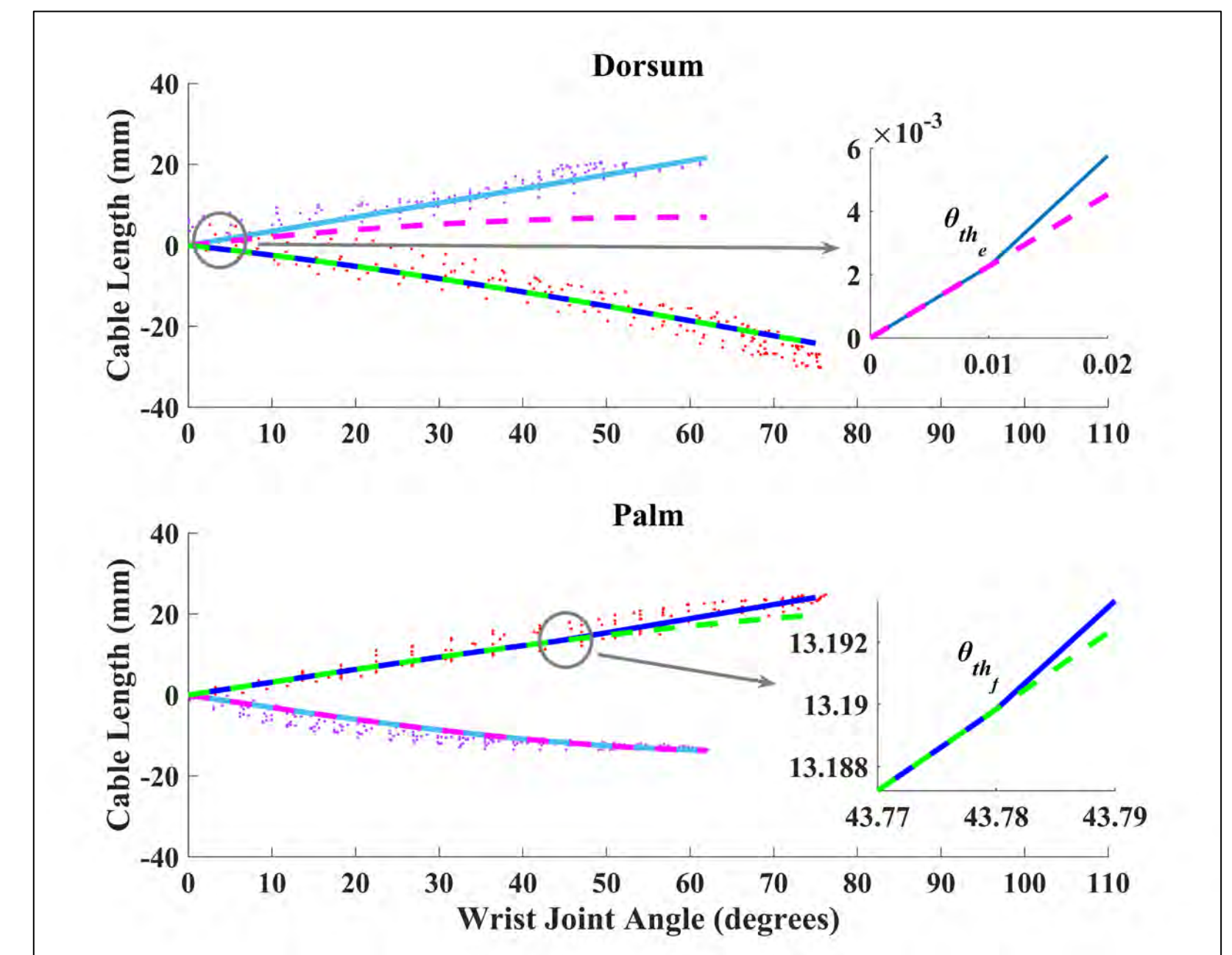


- The **positions** of the guides at the **index finger MCP joint** in the plane of flexion–extension motion.



Correlation: 0.90 ± 0.01

- The variation of **tendon length** during wrist flexion–extension motion.



Conclusions

- In this study, an accurate kinematic model for a tendon-driven WTSD was derived and validated to represent real sheath displacement during hand motion, in order to achieve better control performance.
- The derived kinematic model of the glove was verified by both simulation and benchtop experiments, and the new model has been validated.
- The results of the experimental evaluation verified the accuracy of the kinematic model. The mean correlation coefficient for the kinematic model is 0.90 ± 0.01 .

Acknowledgement

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TOPIC: Rehabilitation and assistive robotics

P-146

Somatotopic sensation in upper and lower limb prosthesis users: A systematic review

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Novel techniques can induce somatotopic sensation in prosthesis users, where sensations are topologically and modality matched to sensors in the prosthesis. This field is relatively new, thus there is little information on the utility of somatotopic sensation, or how best to induce it. We therefore conducted a systematic review to determine what methodologies are effective in eliciting somatotopic sensation, the quality of those sensations, and how the usefulness of sensation was assessed.

We searched PubMed and Web of Science from 1991-2021, finding 38 papers that described somatotopic sensation experiments in a total of 74 participants.

The papers used a variety of stimulation approaches ranging from surface stimulation to intraneural stimulation. Stimulation parameters varied between studies and technologies, but the most common ranges were stimulation amplitudes 0.01-2.5 mA, frequencies 1-500 Hz, and pulse widths 1-250 μ s. Of the 63 participants that described sensation quality, most reported feelings of pressure, paresthesia, or vibration ($n=52,48,40$) while less than half ($n=29$) reported proprioception. A majority of papers ($n = 33$) quantified the effect of sensation on functional tasks such as force matching ($n = 19$) or object identification ($n = 13$), finding improvements in performance when sensation was provided. Only 15 studies observed the stability of percept intensity, quality, or location over multiple sessions, and only 14 studies quantified the effects of stimulation on pain or prosthetic embodiment.

Together, this literature suggests that sensation can be generated and used to improve functional outcomes through several approaches of various invasiveness. We found common parameters that can be used to induce sensation, though optimal parameters may vary by method or participant. We also highlighted the gap in collecting psychosocial and stability metrics, which directly influence the clinical efficacy of somatotopic sensation in prosthetics.

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TOPIC: Rehabilitation and assistive robotics

P-147

Effects of Environmental Intervention on Learning and Performance in a Novel Motor Skill Task

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Despite the abundance of research on motor learning, we still have a limited understanding of how novel real-world motor skills are learned and the best ways to teach these skills. Building upon the recent progress in the field of reinforcement learning, specifically in designing a curriculum for training artificial agents[1], our long-term goal is to develop methods for designing curricula, mediated by technology, including robots, for systematically teaching motor tasks to human participants. In this work, we examine the effects of environmental intervention on task performance using a previously introduced platform, Reach Ninja '[2]. The baseline task requires subjects to interact with a dynamic reaching environment where target markers move in a predictable projectile motion. Preliminary results showed that participant performance improves significantly with practice. Additional interventions are introduced in the form of (a) partial feedback of the subjects' movement, (b) mirroring of movement and (c) interaction between the subjects' tracked marker and the targets on screen. These challenges force subjects to modify their motor behavior compared to that in the baseline task and thus present opportunities in the design of tasks aimed at selectively teaching behaviors. Our results validate the potential of the Reach Ninja task as a platform for studying the learning process of challenging motor skills and the role of these interventions as a means to modulate the level of difficulty and skills learned. In future work, we plan to administer these and other interventions in a controlled order with the goal of improving learning efficiency for a cumulative target task that may or may not include the same interventions. Curriculum-based motor training might be beneficial not only to better understand and control learning of motor tasks in healthy participants, but also to designing rehabilitation protocols for participants surviving neurological impairments.

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TOPIC: Rehabilitation and assistive robotics

P-148

Inter-digit coupling changes during active finger motion post stroke, a preliminary study

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Background

Stroke is the main cause of adult disability in the United States. Multiple biomechanical chains between our joints exist and are well documented. Perhaps the most complex is the one that ties the digits of our hands together. These biomechanical relationships are severely compromised following stroke. In this work we investigate the changes post stroke to the coupling characteristic of each digit during active individual digit motion

Methods

We extensively modified a commercially available device, the Hand of Hope. These changes enabled us to have both position and force feedback for each individual digit. We also developed a custom controller and software. During the experiments, the device is attached to the subject's hand with each digit servo controlled. The subject was asked to move one single digit at a time while all the others were kept locked by the motors. To ensure that the patient is free to move the targeted digit, an impedance control algorithm actuated the motor to assist the movement, based on the current force and position. During each trial, the force generated at each digit was measured. This protocol enabled us to evaluate how much inter-digit coupled force was generated by both healthy and stroke survivor subjects at all digits when they are asked to only move one. The coupling between the 5 digits is presented in a 5 by 5 matrix, the active coupling matrix.

Results

In general, from the preliminary data, we can see a distinct increase in the coupled force generated at the no-target digits, as well as, and perhaps more interestingly, we could also note that the direction of these relationships was sometimes reversed in the stroke survivors.

Conclusions

In this work we have accurately characterized the differences in inter-digit coupling between healthy and stroke survivor subjects. The results may help improve our understanding of the effects of stroke, which would enable the development of more effective therapeutic strategies.

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TOPIC: Rehabilitation and assistive robotics

P-149

Assessment of Upper-body Movement Quality Using Harmony Exoskeleton

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Monitoring changes in motor behavior during rehabilitation is critical for determining the most effective approaches to increase independence of patients with motor impairments. Upper-body robotic exoskeletons have built-in sensing capabilities that enable them to serve as a tool for both training and assessment for upper-body rehabilitation. To accurately measure kinematic parameters, a robotic exoskeleton must be capable of tracking motions at the level of complexity of the joints and must not interfere with the wearer's natural movements. But the biomechanical complexity of the human shoulder poses a challenge for the development of devices that fulfill these assumptions. Prior devices have limited support for the shoulder and limited low-impedance performance due to reflected motor inertia and friction. This may induce unintended reaction forces and residual dynamics that can interfere with wearer's movements. The bilateral upper-body Harmony exoskeleton [1] is capable of full shoulder articulation as well as elbow flexion-extension and wrist pronation-supination motions with high-performance low-impedance behavior. In this study, we examined Harmony's ability to accurately assess Cartesian-space kinematic parameters associated with the wearer's movement quality. Nine healthy participants executed point-to-point movements with and without the presence of the robot and in a fast and a slow speed. Ground-truth was acquired with an optical motion capture, and we extracted the kinematic parameters from the measured data. The results suggest that Harmony can accurately measure kinematic parameters associated with movement quality, and these parameters could appropriately reflect wearer's natural movements in slow speed. Therefore, Harmony could aid the evaluation of the effectiveness of different interventions that is more sensitive and efficient than currently adopted clinical outcomes. This allows for individualization of treatment plan and detailed follow-up.

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TOPIC: Rehabilitation and assistive robotics

P-150

Simultaneous Real-Time Control of Hand Pose and Grasp Strength with an EMG-Driven Hand Exoskeleton

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¹: The University of Texas at Austin

Electromyography (EMG)-driven hand exoskeletons have been developed to assist individuals with hand disabilities, including those surviving a spinal cord injury (SCI), to complete daily activities. While designs of existing exoskeletons support many hand tasks, controllers for these systems place limitations on achievable poses [1] (e.g., opening and closing only) and do not allow for varying the grasp tightness or grasping force [2], thus limiting the subject's ability to seamlessly work with delicate and heavy objects. To address these limitations, we utilize a machine learning-based approach for estimating intended hand pose (chosen from a set of widely used hand poses, namely extension, transverse volar grip, lateral pinch, or extended grip), as well as intended grasping force based on EMG signals. We then develop a control method for the Maestro hand exoskeleton to assist the subjects in achieving the intended grasping pose while varying the grasp stiffness based on the estimated intended grasping force using impedance control. Previous research with the Maestro exoskeleton has demonstrated that because of its three finger modules, eight degrees of freedom, and compliant actuation, it can support multiple grasping poses required in activities of daily living (ADL)[3]. In this work, we show that through the assistive control, subjects can successfully activate the intended grasping pose and pick up objects used in ADL. Moreover, they are able to vary their grasping force to follow a desired force trajectory using the EMG-based assistive exoskeleton and the proposed control algorithm.

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This work was supported by: A portion of this work has taken place in the ReNeu Robotics Lab, The University of Texas at Austin. The research in the ReNeu Lab is supported in part by grants from the National Science Foundation (CMMI 2019704 and 1941260) and Facebook.

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TOPIC: Rehabilitation and assistive robotics

P-151

Kinematic Compatibility of a Wrist Robot with Cable Differential Actuation: Effects of Misalignment Compensation via Passive Joints

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Kinematic incompatibility due to misalignments between robotic joints and human joints leads to parasitic interaction loads between exoskeleton and user, resulting in pain or damage to the user's skin or joints [1]. It is possible to mitigate these effects by incorporating connecting the robot to the user via passive fixations [2]. However, the inclusion of passive joints increases device complexity and impedance; there is thus a trade-off between two conflicting exoskeleton design objectives: 1) ensuring low impedance; and 2) minimizing the effects of misalignments [3]. This trade-off has not yet been studied in wrist exoskeletons.

To investigate this trade-off we developed the UDiffWrist (UDW): a low-impedance 2-DOF wrist exoskeleton featuring a cable-differential transmission. Two versions of the robot were developed: The UDW-C, which achieves kinematic compatibility only with perfect alignment between human and robot joints; and the UDW-NC, which connects the human and robot via passive joints to achieve kinematic compatibility regardless of alignment. For each device, we performed a set of characterization experiments to determine the effect of robot design on system transparency, torque transfer accuracy, and robustness to misalignments.

Mixed model analyses showed that the UDW-NC was more robust to misalignments, as user-interaction torques increased with misalignment in the UDW-C to a greater extent than in the UDW-NC ($p=0.003$). However, the UDW-NC displayed greater Coulomb friction than the UDW-C ($p < 0.001$). Further, Coulomb friction increased to a greater extent in the UDW-NC in the presence of misalignments ($p < 0.001$). The UDW-NC also displayed significantly less accurate torque transfer capabilities. These results suggest that for small range of motion tasks, the mitigation of misalignment effects associated with the incorporation of passive degrees of freedom are overshadowed by the intrinsic drawbacks relating to impedance and torque transfer accuracy.

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TOPIC: Rehabilitation and assistive robotics

P-152

Mirror robotic therapy rehabilitation of wrist and forearm: Pilot study

Alvarez-Pastor, Jesus 1; Martinez-Pacual, David 1; Ezquerro, Santiago 1; Catalan, Jose M-™ 1; Garcia-Perez, Jose V. 1; Mas, Gemma 2; Perez-Pomares Maria Victoria 2; Garcia-Aracil, Nicolas 1
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This paper presents a pilot study of a robotic mirror therapy system for rehabilitation of wrist and forearm. First, the paper presents a novel exoskeleton robotic device with only one actuator to control forearm and wrist motions. This arm wrist exoskeleton has been designed incorporating a patented novelty with which it is possible to actuate the three joints with one DC motor. This invention draws the following advantages for rehabilitation therapies: lighter and less voluminous robotic devices; reduced energy consumption, reducing costs and more affordable robotic devices. Then, the results of a pilot study with 10 patients with different neurological conditions are presented.

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TOPIC: Rehabilitation and assistive robotics

P-153

Physiological reaction to competitive rehabilitation game assisted by robotic devices: Pilot study with patients

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The enhancement of patient 's motivation and the increase of the intensity of rehabilitation therapies are key issues to improve motor recovery. Interpersonal rehabilitation games, compared to single-player games have shown good results in enhancing patient 's motivation and increasing intensity of therapy. Understanding the patient 's physiological reactions to this kind of therapies is a key point to adapt the assistance provided by the robotic devices during this kind of therapies. In this paper presents a pilot study with patients performing competitive rehabilitation games assisted by two robotic devices to understand patient 's physiological reactions in a competitive rehabilitation game

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TOPIC: Rehabilitation and assistive robotics

P-154

A Biofeedback System for Improving Gait Performance in People with Spinal Cord Injury while Using a Wearable Exoskeleton

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Gait rehabilitation for people with spinal cord injury (SCI) is progressing towards robotic systems that offer higher precision, and more repeatable and continuous movements. Recently, robotic gait therapy is focusing on wearable lower-limb exoskeletons since they offer more active participation of the user. However, learning to use a robotic exoskeleton needs time and effort [1].

People with SCI not only lose the ability to control their muscles, but also sensory information. Therefore, sensing the state of their body during walking, which is a requirement in most cases to be capable of controlling a robotic exoskeleton, can be challenging for some users [2].

To this end, we are developing a biofeedback system to help people with SCI to walk and stand while using a wearable lower-limb exoskeleton, and reduce the time and effort needed to learn how to use it. The biofeedback system gives information about different gait metrics to improve gait performance.

We have created an initial prototype of the biofeedback system. The system consists of a back box containing the microprocessor and drivers; and 2 bracelets (one in each arm) with 4 linear resonant actuator (LRA) vibration motors and 1 buzzer each. The biofeedback system gets data from the exoskeleton and/or from instrumented insoles, which are provided to the user through vibratory and/or auditory stimuli.

Thus far, we have focused on understanding the preferences of people with SCI for receiving feedback while walking with a wearable lower-limb exoskeleton. A questionnaire about the type of gait metrics, type of stimuli, and body areas to receive the stimulus was sent to 8 people with SCI. For this purpose, we designed 7 vibroacoustic types of feedback for giving information about 5 different gait metrics.

Finally, a pilot testing with one subject with SCI was conducted as a first validation of the system. Based on the lessons learned, a new version of the biofeedback system is currently being developed.

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TOPIC: Rehabilitation and assistive robotics

P-155

Neural Control Enables Stand-Up, Squat, Lunge, and Walk With a Robotic Knee and Ankle Prosthesis

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Emerging robotic knee and ankle prostheses present an opportunity to restore the biomechanical function of missing biological legs, which is not possible with conventional passive prostheses [1]. However, challenges in coordinating the robotic prosthesis movements with the user's neuromuscular system limit the real-world viability of these devices. Existing controllers use pre-planned prosthesis actions that cannot adapt to the user and environment [2]. Switching between ambulation activities requires to explicitly classify the user's intended movements online. Any misclassification can cause the prosthesis to behave unpredictably, causing the user to fall [3]. Our study shows that a shared neural control approach combining neural signals from the user's residual limb with robot control improves functional mobility in two individuals with above-knee amputation. The proposed shared neural controller enables subjects to stand up and sit down under a variety of conditions, squat, lunge, walk, and seamlessly transition between activities without explicit classification of the intended movement. No other available technology can enable individuals with above-knee amputations to achieve this level of mobility. Further, we show that compared to using a conventional passive prosthesis, the proposed shared neural controller significantly reduced muscle effort in both the intact limb (21 and 51% decrease for participants 1 and 2, respectively) and the residual limb (38 and 48% decrease). We also found that the body weight lifted by the prosthesis side increased significantly while standing up with the robotic leg prosthesis (49% and 68% increase), leading to better loading symmetry (43 and 46% of body weight on the prosthesis side). By decreasing muscle effort and improving symmetry, the proposed shared neural controller has the potential to improve amputee mobility and decrease the risk of falls compared to using conventional passive prostheses.

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TOPIC: Rehabilitation and assistive robotics

P-156

Model Predictive Control for active-assisted hand rehabilitation using an EMG-driven exoskeleton

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The cerebrovascular accidents (CVA) are one of the most common causes of hand motor disability. Rehabilitation therapies with reliable repetition of movements allow the gradual recovery of the mobility. In particular, robotic rehabilitation is a recent alternative to improve the rehabilitation process as it could increase the intensity and frequency of the therapy, provide an accurate control of the motor assistance, and make an objective measurement of the patient progress. In this study, we propose a predictive adaptive control system for a robotic exoskeleton in order to compensate for the effects of muscle effort in hand joint rehabilitation. A dataset of electromyographic signals (EMG) from stroke patients was used to determine the trajectory of the movements, for three levels of muscle effort. Second, a predictive adaptive control technique was implemented to track the specific joint trajectory on a CAD model of the exoskeleton with an error $MSE < 10^{-6}$. Finally, the behavior of the control system was evaluated on the exoskeleton test-bed giving a comparable error ($MSE < 10^{-6}$). The system considers an estimation of the driven speed according to the EMG-based muscular effort detected, which could improve the rehabilitation therapy.

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TOPIC: Socially interactive robotics

P-157

Engineering Autonomous Robotic Solutions for Older Adults in Long-Term Care Facilities

Panchea, Adina M. 1; Maheux, Marc-Antoine 1; Letourneau, Dominic 1; Godin, Cedric 1; Labbe, Mathieu 1; Ferland, François 1; Grondin, François 1; Michaud, François 1

1 : IntRoLab - Intelligent, Interactive, Integrated and Interdisciplinary Robotics Lab, Interdisciplinary Institute for Technological Innovation (3IT), Department of Electrical Engineering and Computer Engineering, Université de Sherbrooke, Sherbrooke, Canada

Even though a great variety of socially assistive robots [1] for older adults care have been designed, tested and evaluated, demonstrating great potential, they still mostly remain research endeavors. Explanations for this are that we still need to find the right application where user expectations and the robot 's capabilities are both met, and that we need to provide compelling evidence to help propel the necessary changes to policies and regulations to support their use in real world settings. To address these issues, we present engineering guidelines and issues to address, such as: deployments over long periods of time are hard, wireless networks are unreliable, hardware-software integration is the key and software infrastructure requires the integration of multiple frameworks. We are following such guidelines in the design of robotic applications, i.e., an autonomous telepresence robot named SAM, Securbot platforms for surveillance purposes, and T-top a companion robot, for older adults in long-term care facilities, along with platforms [2] and tools [3] we have been developing to bring robots for experimenting in those facilities. By demonstrating and experimenting different robots and capabilities, we believe that showing their strengths and weaknesses in real world settings will accelerate the emergence of ideas about potential usages, identify new capabilities to develop or transfer, and facilitate the integration of these robots in care facilities. We currently have two different standard telepresence robot platforms deployed in one long-term care facility, allowing users (health personnel, caregivers and older adults) to experiment with non-autonomous robot platform. Finally, open source solutions are also presented to facilitate integration of hardware and software for telepresence robots and will allow the research community avoid "reinventing the wheel" and provide the opportunity for other researchers to contribute to the effort.

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TOPIC: Rehabilitation and assistive robotics

P-158

Powered Hip Exoskeleton Increases Self-Selected Walking Speed in Stroke: A Case Study

Ishmael, Marshall; Archangeli, Dante; Lenzi, Tommaso

University of Utah, Salt Lake City, USA; University of Utah, Salt Lake City, USA; University of Utah, Salt Lake City, USA

Tens of millions of people affected by a stroke every year have long-term disability, reducing walking speed and mobility [1]. Powered exoskeletons have the potential to address this problem by assisting users during ambulation. Studies have shown that providing propulsion assistance distally at the ankle improves self-selected walking speed [2]. However, it is not known whether proximal assistance at the hip improves self-selected walking speed. This case study investigates the effect of a lightweight powered hip exoskeleton on self-selected speed and hip kinematics in one subject with chronic stroke. The participant performed the 10-meter walking test (10MWT, self-selected speed) with and without the exoskeleton six times while we recorded kinematics. The powered exoskeleton assisted the hemiparetic leg only, providing flexion torque during late stance and early swing in synchrony with the movements of the user's leg [3]. The exoskeleton did not assist extension. Self-selected walking speed was 29.6% faster with the exoskeleton, increasing from 0.54 m/s without the exoskeleton to 0.70 m/s with the exoskeleton (two-tailed paired t-test, $p = 1.4 \times 10^{-6}$). The time to complete the 10MWT with the exoskeleton was 8.6 ± 0.37 s (mean \pm standard deviation) down from 11.1 ± 0.41 s without the exoskeleton. Our kinematic analysis shows that the faster self-selected speed was primarily due to the participant taking longer strides. The subject took 12 strides to complete the 10MWT without the exoskeleton while only needing 10 strides with the exoskeleton. Accordingly, the range of motion of the impaired hip joint was 48.6% larger with the exoskeleton than without the exoskeleton (43.78° vs. 29.46°). By improving self-selected walking speed, our powered hip exoskeleton shows promise as a viable solution to improve the mobility of individuals suffering from the long-term disability caused by stroke.

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TOPIC: Robotics for clinical practice

P-159

Comparison of Walking with a Knee-Ankle-Foot-Orthosis (KAFO) and a Powered Knee Exoskeleton in People with Spinal Cord Injury: A Randomized Crossover Clinical Trial

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People with a spinal cord injury (SCI) are restricted to a sedentary lifestyle due to the loss of the ability to stand or walk. This lack of physical activity increases the risk of developing secondary health conditions, which can further reduce their life expectancy [1]. Therefore, independent standing and walking present numerous benefits for people with SCI.

Knee-ankle-foot orthoses (KAFO) are passive devices that allow people with SCI to walk and stand. While KAFOs are frequently used in clinical practice, their use for functional mobility is controversial and physically demanding, since they require considerable effort to perform steps [2].

In response to the limitations of KAFO, wearable exoskeletons are emerging as an alternative technology for gait rehabilitation as they may augment gait efficiency, and provide safer walking compared to KAFO. However, there is a lack of evidence that supports the superiority of wearable exoskeletons over KAFO.

To this end, we are carrying out a randomized crossover clinical trial (NCT04855916) with 10 people with SCI (T4-T12) that had previous experience with KAFO. Participants are carrying out 10 gait training sessions with their KAFO and with the ABLE Exoskeleton (ABLE Human Motion, Spain). In sessions 5 and 10, participants carry out three standardized clinical tests (i.e., TUG, 10MWT, and 6MWT). The main outcome measure is the gas exchange during the aforementioned clinical tests. Secondary outcome measures include spatiotemporal gait parameters, gait kinematics, perceived level of exertion, and questionnaires on usability, user satisfaction, and psychosocial impact. Data collection is currently ongoing and study completion is expected in September 2021.

We hypothesized lower oxygen consumption, a reduction of compensatory movements, and higher scores for the clinical tests when walking with the ABLE Exoskeleton compared to the KAFO. We aim at presenting a preliminary analysis of the results at the RehabWeek 2021.

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TOPIC: Rehabilitation and assistive robotics

P-160

Design and Amputee Testing of an Adaptive Stair Ascent Control for Powered Knee and Ankle Prostheses

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1: University of Utah

Powered prostheses can enable individuals with above-knee amputations to ascend stairs step-over-step, which is not possible with conventional passive prostheses. To accomplish this task, available stair ascent controllers for powered prostheses impose a pre-defined joint impedance behavior or follow a pre-programmed position trajectory. These control approaches have proved successful in the laboratory. However, they are not robust to changes in stair height, gait pattern, or cadence, which is essential for real-world ambulation. Here we present an adaptive stair ascent controller that continuously adapts to the movements of the user's residual limb to enable climbing stairs of varying stair heights at user preferred cadence and with user preferred gait pattern. In swing, the movement of the prosthesis adapts to the movement of the user's thigh based on thigh angle, rotational velocity, and vertical acceleration. In stance, the knee extension torque-angle relationship is automatically adapted based on the knee angle at heel strike. We implemented the proposed controller on a lightweight powered knee and ankle prosthesis [1], [2] and tested with one individual with above-knee amputation. Using the proposed adaptive stair controller, the participant was able to climb stairs with two stair heights (4' and 7' ADA compliant standards) and three gait patterns (step-by-step, step-over-step, two steps at a time) at his preferred cadence (swing duration of 0.85-1.67 seconds). Kinematic analysis shows that the adaptive swing controller provided sufficient clearance for all conditions. Additionally, the adaptive stance controller increased the net mechanical energy injection proportionally to the step-height, imitating the behavior of the biological leg. The proposed adaptive stair controller may improve the robustness of powered prostheses to environmental and human variance, enabling powered prostheses to more easily move from the laboratory to the real-world.

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TOPIC: Rehabilitation and assistive robotics

P-161

A Lightweight, Compact Powered Knee Prosthesis with Elastic Torque-Sensitive Actuation

Tran, Minh 1; Gabert, Lukas 1; Lenzi, Tommaso 1;
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Millions of individuals live with an above-knee amputation worldwide [1]. Virtually all available knee prostheses are energetically passive, but ambulation requires positive power generation and active control of movements. As a result, ambulating with passive prostheses is challenging, particularly with tasks that require substantial positive power generation at the knee joint, such as ascending stairs or standing up from a chair. Powered leg prostheses have been developed to address these issues, and promising results have been reported in the laboratory. However, the ability of powered prostheses to generate positive power and actively control movements comes at the cost of increased mass and size, significantly limiting their clinical viability [2]. To address the limitations of available powered prostheses, we developed a novel torque-sensitive actuator, which combines the benefits of elastic actuators and variable transmissions. By passively and automatically adapting the transmission ratio to the external load, the proposed torque-sensitive actuator operates closer to its optimal efficiency during all ambulation activities, enabling the use of much smaller structural and servomotor components. We implemented the proposed actuator on a fully powered knee prosthesis that matches, for the first time, the weight and dimensions of passive microprocessor-controlled prostheses (1.5 kg). Notably, all mechanical and electrical components are fully enclosed in the prosthesis, which is designed to satisfy ISO standards. Experiment results with one amputee subject ambulating on level ground and stairs show that the proposed powered knee prosthesis can replicate the biomechanical functions of the biological knee. By combining the lightweight and small dimensions of passive prostheses with the power generation and active control abilities of powered prostheses, the proposed device may provide a level of mobility that is not currently possible with existing devices.

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TOPIC: Rehabilitation Technology and Implementation Science

P-162

A Day in the Life: A Qualitative Study of Clinical Decision-Making and Uptake of Neurorehabilitation Technology

Celian, Courtney 1; Swanson, Veronica 2; Shah, Maahi 3; Newman, Caitlin 4; Fowler-King, Bridget 5; Gallik, Sarah 6; Reilly, Kaitlin 7; Reinkensmeyer, David J. 8; Patton, James 9; Rafferty, Miriam R. 10
1 Shirley Ryan AbilityLab, Chicago, USA; 2 Department of Mechanical and Aerospace Engineering, Henry Samueli School of Engineering, University of California, Irvine, USA; 3 Department of Bioengineering, University of Illinois at Chicago, Chicago, USA; 4 Department of Anatomy and Neurobiology, UC Irvine School of Medicine, University of California, Irvine, USA; 5 Department of Physical Medicine and Rehabilitation, Northwestern University Feinberg School of Medicine, Chicago, USA

Despite the ongoing development of rehabilitation technology (RT), there is limited clinical acceptance of new technologies in neuro-rehabilitation treatment. Our aim was to examine clinical uptake to inform developers of RT of the clinical decision-making surrounding therapists' choice to use, or not use, RT during treatment.

A phenomenological qualitative approach was used, with three occupational therapists and two physical therapists employed at a major rehabilitation hospital. They were asked to write vignettes describing their RT use during their treatment sessions, obtaining information on nine patients (4 with stroke, 2 traumatic brain injury, 1 spinal cord injury, 1 with multiple sclerosis). We then coded these vignettes using deductive qualitative analysis from 17 constructs derived from the Consolidated Framework for Implementation Research (CFIR). Data were synthesized using Summative Content Analysis.

The five main constructs reported were (i) relative advantage, (ii) personal attributes of the patients, (iii) clinician knowledge and beliefs of the device/intervention, (iv) complexity of the devices including time and setup, and (v) organizational readiness to implement. RT often was not used compared to conventional treatment, due to its lack of connection to "functional" tasks, its complexity of use, and the increased time for setup. RT was not transferable to diverse patient groups, including complex diagnoses, and physical and cognitive limitations. This was especially true in the acute phase of recovery where the primary focus of rehabilitation was returning to activities of daily living. Finally, organization-sponsored training and standardizing operational processes made it easier for clinicians to adopt RT.

RT development is a delicate process that must consider multi-faceted views before integration into rehabilitation. Most notably, the intervention itself, the people involved, as well as the organizations' implementation climate.

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A day in the life: A qualitative study of clinical decision making and uptake of neurorehabilitation technology



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Courtney Celian, Veronica Swanson, Maahi Shah, Caitlin Newman, Bridget Fowler-King, Sarah Gallik, Kaitlin Reilly, David J. Reinkensmeyer, James Patton, Miriam R. Rafferty

Introduction

BACKGROUND

Despite the ongoing development of rehabilitation technology (RT), there is limited clinical acceptance of new technologies in neuro-rehabilitation treatment.

PURPOSE

To examine clinical uptake to inform developers of neuro-technology of the clinical decision-making surrounding therapists' choice to use, or not use, RT during treatment.

Qualitative Methods

We used vignettes to understand clinicians' real-time decision-making process in the moments when they are choosing to use or not use RT with their patients.

SUMMATIVE CONTENT ANALYSIS

We coded barriers and facilitators using Consolidated Framework for Implementation Research (CFIR).

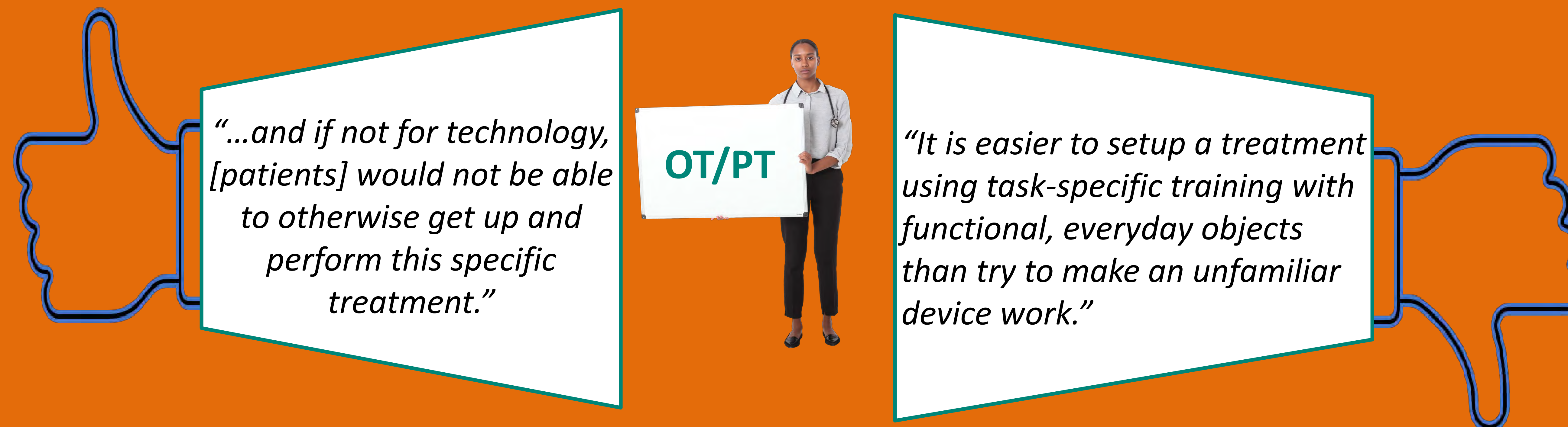
CFIR Construct
Definitions



Click here for
Manuscript and
Vignettes



Rehabilitation technology needs to be functionally relevant and simple for increased clinical uptake



Results

Nine vignettes provided by five therapists (six OTs, three PTs) for patients with TBI (n=2), SCI (n=1), stroke (n=4), and MS (n=1).

17 of 39 CFIR constructs were mentioned.

There were a total of 174 statements coded in the vignettes.

Clinical Bottom Line

Rehabilitation Technology

Should...

- Relate to functional tasks
- Be simple and fast to setup
- Be applicable to various patient diagnoses
- Be incorporated into clinical training
- Transfer into the organization's implementation climate

Acknowledgements

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Construct	# of Clinicians (of 5) Mentioning	# of Vignettes (of 9) Mentioning	Total number of times mentioned (of 174)
Relative Advantage	5/5 (100%)	9/9 (100%)	32 (18.4%)
Complexity	5/5 (100%)	9/9 (100%)	16 (9.2%)
Clinician Knowledge and Beliefs	5/5 (100%)	7/9 (77.8%)	18 (10.3%)
Implementation Climate	5/5 (100%)	5/9 (55.6%)	6 (3.4%)
Adaptability	3/5 (60%)	4/9 (44.4%)	7 (4.0%)
Patient Knowledge and Beliefs	2/5 (40%)	3/9 (33.3%)	4 (2.3%)

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TOPIC: Rehabilitation and assistive robotics

P-163

Powered Knee Exoskeleton With Proportional EMG Control Improves Sit-to-Stand Transition Symmetry in a Stroke Subject

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Stroke affects the mobility of millions of individuals worldwide. After a stroke, the ability to stand up from a chair is severely reduced. Because of muscle weakness on the impaired side, many stroke victims show asymmetrical weight-bearing patterns during sit-to-stand transitions, deteriorating balance, and increasing the risk of falls. In theory, powered exoskeletons can address this problem by assisting the impaired limb during sit-to-stand transitions. However, there is no experimental evidence demonstrating the efficacy of this intervention. To address this gap, we implemented a proportional electromyography (EMG) controller [1] in a powered knee exoskeleton [2] and tested sit-to-stand transitions with a single hemiparetic subject. The powered exoskeleton provided knee extension torque to the affected side proportionally to the EMG signal of the participant's affected quadriceps. The participant performed ten sit-to-stand transitions with and without the knee exoskeleton while we measured the subject's kinematics and ground reaction forces. Our results show that the powered knee exoskeleton significantly improved the participant's weight-bearing symmetry (Paired t-test, $p = 0.4555$). Specifically, the Degree of Asymmetry [3] decreased from 10.46% without the exoskeleton to 1.14% with the exoskeleton. This improvement was primarily due to the substantial increase in the impaired-side GRF, which increased from 420.4 ± 16.2 N without the exoskeleton to 535.6 ± 31.5 N with the exoskeleton. Moreover, the knee joint velocity on the impaired side increased from 144.1 ± 8.9 $^\circ/\text{s}$ without the exoskeleton to 246.5 ± 17.4 $^\circ/\text{s}$ with the exoskeleton. Their sound side showed a similar trend without and with the device, 137.4 ± 7.8 $^\circ/\text{s}$ to 189.5 ± 11.9 $^\circ/\text{s}$, respectively. This case study suggests that powered knee exoskeletons can successfully assist individuals with chronic stroke by improving weight-bearing symmetry and allowing for faster movements during sit-to-stand transitions.

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TOPIC: Human-machine interfaces in rehabilitation

P-164

Comparing Sonomyography and Electromyography Using Bayesian Regression to Continuously Estimate Joint Torques During Ambulation on Varying Terrains

Kaitlin G. Rabe 1; Tommaso Lenzi 2; and Nicholas P. Fey 1

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2: University of Utah, Salt Lake City, Utah, USA

Next-generation assistive devices that can restore locomotor abilities are essential to improve the reintegration of individuals with mobility impairments and/or limb loss within society [1]. However, these devices often lack control interfaces that seamlessly incorporate the volition of their users in a task-agnostic and targeted (i.e. joint-specific) manner [2]. To address these limitations, we tested the hypothesis that real-time ultrasound imaging of muscle contraction, or sonomyography, improves joint torque prediction compared to surface electromyography (EMG). Previously, we demonstrated sonomyography can continuously classify ambulation modes with >99% accuracy [3]. However, it is unknown if SMG of thigh musculature can be used to continuously estimate multiple joint torques during ambulation on multiple terrains. Ten able-bodied subjects completed level, incline (10– ∞), and decline ambulation one-minute trials. Subjects donned a wearable ultrasound transducer that recorded transverse images of superficial and deep anterior thigh muscles. EMG signals were collected from eight ipsilateral leg muscles. Gaussian processes regression models were trained to continuously predict hip, knee and ankle joint moments (with ground truth data computed via inverse dynamics and dynamic motion capture) using features extracted from sonomyography and EMG in a task-independent and user-dependent paradigm. Sonomyography improved regression performance during all tasks to 8.0% root mean square error at the hip, 6.1% at the knee and 4.6% at the ankle compared to 11.7%, 10.4% and 9.4% at the hip, knee and ankle using EMG, respectively. Thus, sonomyography of the thigh musculature can be used to continuously estimate required torque of multiple lower-limb joints during varying ambulation conditions, using a task-independent Bayesian regression approach. These techniques could transform traditional control strategies of intelligent assistive technologies and improve human ability.

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TOPIC: Rehabilitation and assistive robotics

P-165

Robust Neural Decoding of Individual Finger Forces over a Multi-Day Evaluation

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Neural-machine interface offers intuitive interaction with assistive robotic hands. A lack of reliability of neural decoding can limit the utility of such assistive devices. Traditional control strategies include continuous electromyogram (EMG) amplitude regression or pattern recognition. The former approach is prone to interference over time, while the latter is limited in a fixed set of movement patterns. Here, we implemented an efficient encoder-decoder convolutional neural network (CNN) structure. High-density EMG signals were used as direct inputs to the encoder, in order to extract neural features from motor unit action potentials in the EMG signals. The decoder then learned the mapping from extracted features to finger-specific populational motoneuron firing frequency. The predicted firing frequencies were then used to estimate finger forces (index, middle, and ring). High-density EMG signals were obtained from finger flexor and extensor muscles over three distinct days. The CNN was calibrated on data from Day 1 and Day 2 to learn the time-dependent variation in the EMG signals. Compared with a channel-wise refined EMG amplitude approach, the CNN has a better performance in the same-day condition (calibrated and evaluated on the same day), and the cross-day condition (evaluated on Day 3). Specifically, in the same-day condition, the CNN showed a lower prediction error (8.16% MVC) than the EMG amplitude approach (13.97% MVC). In the cross-day condition, the CNN had a similar prediction error (9.21% MVC) compared with the same-day condition. In contrast, the EMG amplitude approach showed a substantial increase in prediction error (17.25% MVC) in the cross-day condition. These findings demonstrated that the CNN approach was more accuracy and more robust over time than the EMG amplitude approach. The results demonstrated that the implemented CNN approach could provide reliable neural decoding for the control of assistive robotic hand during long-term use.

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TOPIC: Rehabilitation and assistive robotics

P-166

Underactuated Powered Ankle and Toe Prosthesis

Gabert, Lukas 1; Tran, Minh 1; Lenzi, Tommaso 1

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Ambulation with existing leg prostheses is slower, less stable, and less efficient than able-bodied ambulation. Powered ankle/foot prostheses aim to address this issue by replicating the biomechanical function of the missing biological limb. During walking, the ankle joint injects a considerable amount of energy into the gait cycle [1], which has motivated the development of many powered ankle/foot prostheses in the last 10-15 years [2]. The analysis of nonamputee biomechanics also shows that the toe joint dissipates energy during walking, affecting ankle power, center of mass power, and push-off work during walking [3]. However, virtually all existing ankle/foot prostheses fail to replicate this important biomechanical function as they have no toe joint. To address this limitation, we developed an ankle/foot prosthesis with active toe and ankle joints. A novel underactuated system mechanically connects the ankle and toe joint, simultaneously providing negative power at the toe joint and positive power at the ankle joint during gait. Instead of dissipating energy at the toe joint, the proposed mechanism transfers the negative toe energy to the ankle joint, allowing for substantial improvements in energy efficiency. As a result, the proposed prosthesis is lightweight (1.5 kg including battery and electronics) and compact (178 mm tall, 60 mm wide). Testing with one individual with leg amputation shows that the proposed ankle/foot prosthesis closely matches biological kinematics and kinetics. On average, in one stride, the ankle injects 0.15 J/kg, the toe absorbs 0.02 J/kg, so the actuation only requires 0.13 J/kg. By replicating the biomechanics functions of both the biological ankle and toe joint, the proposed ankle/foot prosthesis has the potential to improve ambulation for individuals with leg amputation.

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This work was supported by: NIH grant #R01HD098154, DOD grant # W81XWH-21-1-0037

REHAB WEEK 2021

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TOPIC: Wearable devices

P-167

Considering the Human Form and its Influence on the Moment- and Power-Generating Abilities of Soft Hip-Flexion Exosuits: Effects of Wearer BMI and Sex

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Soft wearable devices known as “exosuits” are capable of delivering assistive power to human wearers through textile-based, form-fitting interfaces that are less obtrusive than those of rigid exoskeletons [1]. By using flexible joint-spanning elements (e.g., Bowden cables) that are actuated to create tension, exosuits assume a geometry unique to each user’s body. While this adaptability is touted as a strength, the effects of different body sizes and shapes on device performance independent of actuation are unknown. In this study, we modeled a hip flexion-assisting exosuit during level walking for a range of user anthropometrics represented by 3D human surface models [2] that are parametrically generated based on body mass index (BMI), height, and sex. We used fourteen surface models to represent a statistical cross-section of the US adult population [3] (7 female, 7 male, BMI of 5th-95th percentile). We developed a custom numerical framework to simulate the deformation of a linear actuator spanning anterolateral and anteromedial surfaces of the torso and thigh, as well as movement of the wearer during a simulated level-ground walking task, using normative gait data. We tested the effect of proximal and distal actuator placement (i.e., surface grids with 5 cm grid spacing) on the mean hip flexion moment arm during 3D motion of body. Then, the mechanical power generated using a nominal configuration of the device and a constant 200 N of tension in the actuator, were compared. Results showed that mass-normalized peak hip flexion power decreased with increasing BMI, and that the device typically generated ~0.2 W/kg more power for female individuals compared to males of the same BMI. This work informs exosuit performance based on actuator placement and human surface geometry, suggesting that user size and shape have significant influence on device function. In the future, this framework could integrate individual body scans and motion data to personalize assistance.

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TOPIC: Rehabilitation and assistive robotics

P-168

An Experimental Protocol to Study Motor Adaptation in Response to Perturbations Generated by a Lower-Limb Exoskeleton

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1: Harvard Medical School, Boston, USA; 2: EPFL, Lausanne, Switzerland; 3: Polytechnique Montreal, Montreal, Canada, 4: Federal University of Espirito Santo (UFES), Vitoria, Brazil

Humans adapt to changes in the environment by generating internal models that are responsible for adjustments in motor plan. This process is referred to as “motor adaptation” (Shadmehr & Mussa-Ivaldi, 1994). The study of motor adaptation during gait is key to achieve a better understanding of the mechanisms underlying the control of human locomotion. Experiments relying on robotics to induce gait perturbations have indicated that motor adaptation aims primarily to preserve gait stability and secondarily to minimize energy expenditure (Cajigas, Koenig, Severini, Smith, & Bonato, 2017). The same set of experiments revealed that humans respond to perturbations in a selective manner, namely they respond to perturbations affecting step length but not step height when walking on a treadmill with their pelvis held in place by the robot. Also, these experiments indicated that the above-stated observations are driven by feedforward control mechanisms. In contrast, during overground walking with no mechanical constraints imposed by the robot on the displacement of the pelvis, one would expect substantial contributions from feedback-loop mechanisms as balance control is required. The study herein presented aims to explore whether the above-mentioned selectivity in motor adaptation that we observed during treadmill walking is also observed during overground walking. To achieve this goal, we plan to use the ExoRoboWalker (Andrade, Sapienza, & Bonato, 2019), a six degree-of-freedom overground lower-limb exoskeleton, to generate gait perturbations like the ones used in our previous experiments with focus on treadmill walking. The ExoRoboWalker was designed to be transparent to the user during the baseline and after-effect portions of the experiment and to generate a perturbation torque during the adaptation phase. Biomechanical and electromyographic data will be collected to study the response to the perturbations generated by the exoskeleton.

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This work was supported by: Bertarelli Foundation

Background

Motor adaptation is the process through which the central nervous system modifies motor commands in a new walking environment [1]. Experiments involving the Lokomat (Figure 1A) to perturbate the gait have proven motor adaptation to be mainly driven by gait stability. They have also shown a response when participants were exposed to perturbations affecting step length, but none when perturbations were affecting step height (Figure 1C) [2]. This selective mechanism of adaption is mainly guided by feedforward control strategies. Suppressing the movement constraint on the pelvis by adopting an overground exoskeleton could result in a significant contribution of reactive, feedback mechanisms to assist in balance control.

Objectives

Explore whether the selective process underlying the generation of motor adaptation observed during treadmill walking with the Lokomat is also observed during overground walking with the ExoRoboWalker.

Methods

The ExoRoboWalker, a six degree-of-freedom overground exoskeleton (Figure 2), will be used to reproduce the experiments performed with the Lokomat.

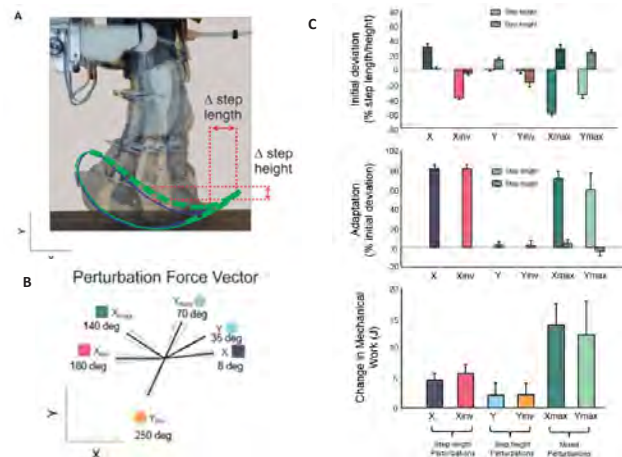


Figure 1: (A) The Lokomat was used to perturbate (green line) the baseline trajectory (blue line). (B) Orientation of the vectors that resulted in the desired effects (X/Xinv: increase/decrease in step length, Y/Yinv: increase/decrease in step height, Xmax/Ymax: maximal deviation in step length/height + effect on step height/length). (C) Summary of the results of the motor adaptation experiments. [2]

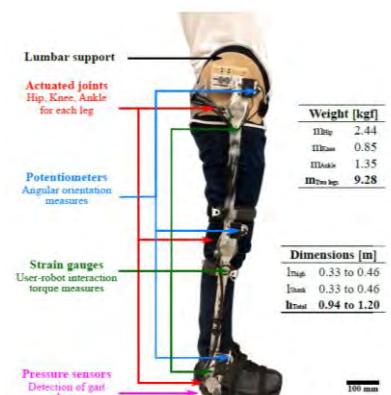


Figure 2: ExoRoboWalker configuration.

A real time target machine (i) receives data on gait biomechanics from the sensors embedded at each joint via a Controller Area Network (CAN) communication bus, (ii) sends output to each motor using its on-board analog and digital I/O (Figure 3).

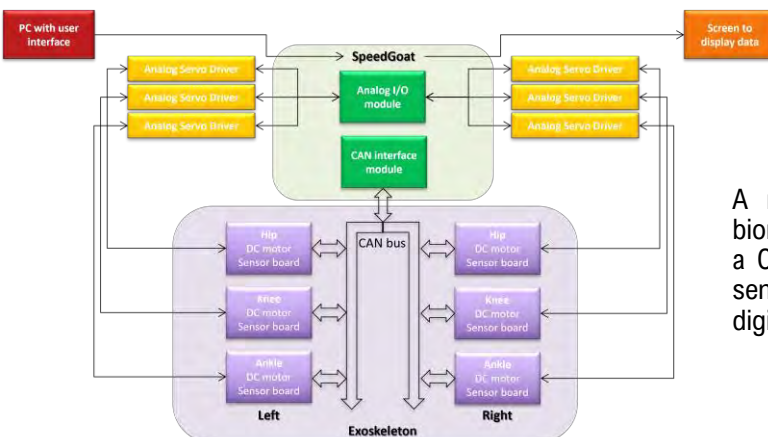


Figure 3: Architecture of the current system.

The control system of the ExoRoboWalker is organized in a hierarchical architecture with a higher-level impedance controller and a lower-level PD torque controller [3] (Figure 4). The exoskeleton is therefore designed to be transparent to the user and minimally interfere with his normal gait when no perturbation is applied (i.e. during the baseline and after-effect phases). During the adaptation phase, perturbations can be applied directly at the level of the ankle. For the study, biomechanical and electromyographic data will be collected to be analyzed.

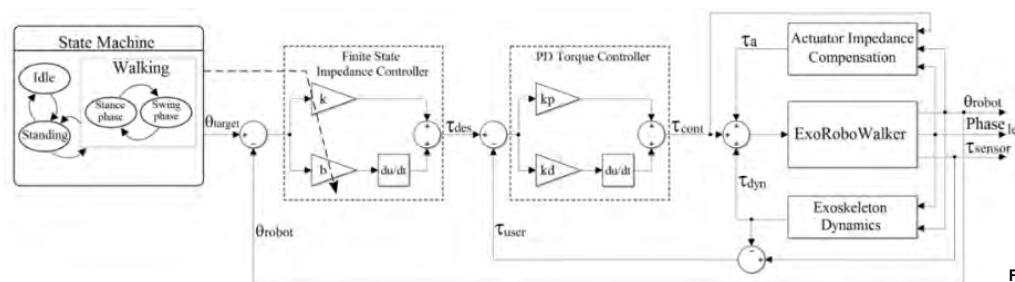


Figure 4: Transparent Operation Mode. [3]

Discussion

While perturbing step height has little influence on balance when the pelvis is restrained, when loosened, it generates an acceleration of the center of mass that can challenge one's long-term stability. With these experiments, we expect a significant contribution of feedback and feedforward mechanisms. Motor adaption should be visible in both step length and step height experiments. Furthermore, as overground lower-limb exoskeletons require the active participation of the user, this could result in the engagement of different muscles when compared to the Lokomat experiments and it could also have an effect on the rapidity of the rehabilitation process.

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TOPIC: Rehabilitation and assistive robotics

P-169

Preliminary Results in Partial Gait Assistance Using the lower Limb Exoskeleton autonomy

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Lower limb exoskeletons are utilized for rehabilitation purposes and/or for daily mobilization. However, most existing control approaches are developed for people suffering from Spinal Cord Injury (SCI) and for stroke survivors [1]. On the other hand, limited research results have been presented for people with partial walking impairments caused by disorders such as muscular dystrophy, and multiple sclerosis. In the case of exoskeletons targeting this population, the assistance strategies and intention detection approaches are two main aspects to provide proper assistance to exoskeleton users.

The exoskeleton autonomy [2] has been designed to assist gait for people with partial gait impairments. An open-loop impedance control strategy has been implemented and through a finite state machine (FSM) to manage the assistance approach throughout the gait cycle. The desired position is varied at 3 levels according to the gait phases such as swing, stance, and double stance. The implemented control approach should provide enough support while still allowing freedom of motion.

The current work concerns a comparative study implementing a variable impedance control assistance approach in 9 healthy participants over 10 meters ground-level walking tests and throughout 2 sessions. We compared 2 strategies to detect the intention of the users to move forward, the first is based solely on ground reaction forces (GRF), whereas the second combines the GRF and the detection of the hip velocity threshold. Two assistance levels have been evaluated by setting up the impedance and equilibrium point values [3]. The results are analyzed and compared in each of the 4 configurations. The effect of the gait detection approach and assistance level on the user's gait is assessed. The cadence, the gait dynamics, the assistance torque, and the regularity of gait will be presented and discussed.

References: Baud, R., Manzoori, A.R., Ijspeert, A. et al. Review of control strategies for lower-limb exoskeletons to assist gait. *J. NeuroEngineering Rehabil* 18, 119 (2021)., [2] A. Ortlieb, M. Bouri, R. Baud and H. Bleuler, "An assistive lower limb exoskeleton for people with neurological gait disorders," 2017 International Conference on Rehabilitation Robotics (ICORR), 2017, pp. 441-446, [3] A. Ortlieb et al., "An Active Impedance Controller to Assist Gait in People with Neuromuscular Diseases: Implementation to the Hip Joint of the AUTONOMYO Exoskeleton," 2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (

This work was supported by: Association ASRIMM, Foundation FSRMM, Company Faulhaber AG, Swiss Society for Multiple Sclerosis.

Introduction

Lower limb exoskeletons are utilized for rehabilitation purposes and/or for daily mobilization. However, most existing control approaches are developed for people suffering from Spinal Cord Injury (SCI) and for stroke survivors [1]. On the other hand, limited research results have been presented for people with partial walking impairments caused by disorders such as muscular dystrophy, and multiple sclerosis. In the case of exoskeletons targeting this population, the assistance strategies and intention detection approaches are two main aspects to provide proper assistance to exoskeleton users.

Methods

Experimental Device – Autonomy Exoskeleton

The exoskeleton autonomy has been designed to assist gait for people with partial gait impairments [2] and is presented in Figure 1. Autonomy is composed of three degrees of freedom (DoF) at each leg as hip and knee flexion/extension and hip adduction/abduction. Three passive DoFs per leg are located about the ankle. The system is interfaced at the foot, the shank, and the trunk of the body. The device weighs about 25 kg and is adaptable to the user's height from 160 cm to 205 cm.

An open-loop impedance control strategy has been implemented and through a finite state machine (FSM) to manage the assistance approach throughout the gait cycle. The desired position is varied at 3 levels according to the gait phases such as swing, stance, and double stance.

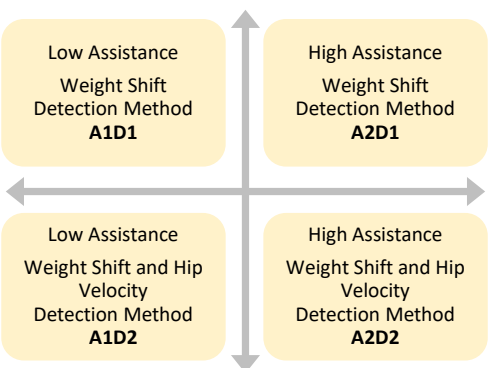


Figure 1. Presentation of degrees of freedoms of autonomy exoskeleton as: Hip abduction/adduction, Hip Flexion/Extension, Knee Flexion/Extension

Experimental Protocol

For the clinical trials, healthy and people with walking impairments are recruited. The participants attended 3 sessions. At first, participants are allowed to walk with an exoskeleton for adaptation. After this period, 10 m walking experiments are conducted in 4 different configurations for the healthy participants.

The current work concerns a comparative study implementing a variable impedance control assistance approach in 9 healthy participants over 10 meters ground-level walking tests and throughout 2 sessions. In the experiments, 2 different assistance configurations such as low (A1) and high (A2) assistance and 2 strategies to detect the intention of the users to move forward, the first (D1) is based solely on ground reaction forces (GRF), whereas the second (D2) combines the GRF and the detection of the hip velocity threshold are tested.



Results

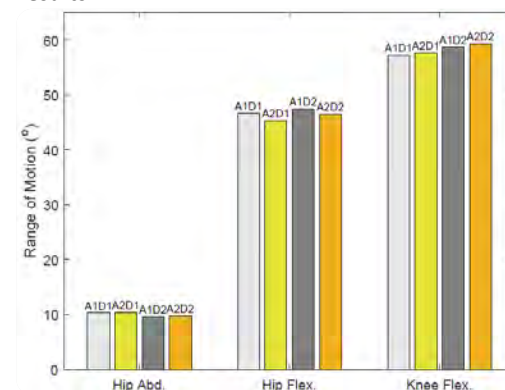


Figure 2. Comparison of range of motion in 4 configurations

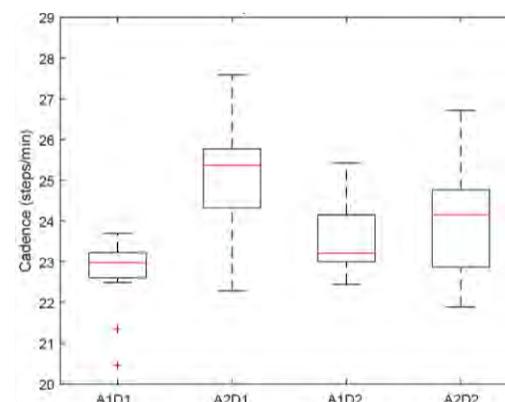


Figure 3. Comparison of cadence values in 4 configurations

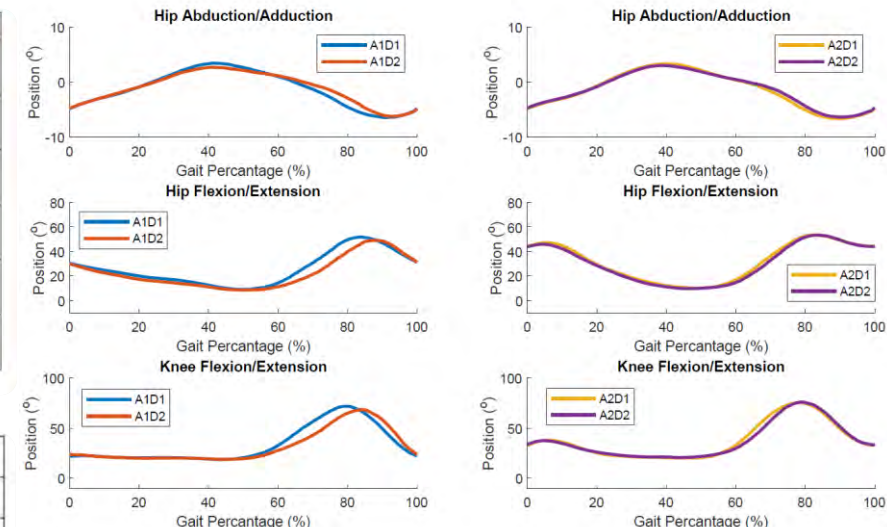


Figure 4. Comparison of position trajectories 2 detection strategies for the same assistance strategies.

As presented in Figure 2, in the comparison of all 4 configurations maximum of 2° of difference is observed in the mean values of the range of motion for all joints.

In all 4 configurations, median cadence values have stayed between 23-25 steps/min while a larger standard deviation is observed with A2 configurations.

In Figure 4, hip and knee flexion/extension position trajectories are affected by the desired positions as expected with A2 configurations. Moreover, from the comparisons of intention detection strategies (A1D1vsA1D2 and A2D1vsA2D2), it has been observed that with D2 detection intention configurations were delayed compared to D1 cases. During the clinical trials, the subjects were also expressed as the D1 strategy is more reactive while, D2 is more synergetic.

Conclusion

1. The implemented controller provides support while still allowing freedom of motion dependent on user intention. Therefore, compared assistance and intent detection strategies did not result in remarkable changes in the range of motion of joints or cadence.
2. Effects of the assistance level of the controller on the human kinematics are more detectable and significant during the loading response and terminal swing phases of the gait.
3. Utilization of hip velocity in addition to weight shift strategy resulted in delayed detection of gait phases.

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Thanks to Dawood Ahmed and Sébastien Muller for their help during the project and during the clinical trials.

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TOPIC: Rehabilitation and assistive robotics

P-170

Training Somatosensation with Proprioceptive Robots and Propriopixels

Reinsdorf, Dylan 1; Johnson, Chris 2; Reinkensmeyer, David 1,2,3

1: Department of Mechanical and Aerospace Engineering, UC Irvine; 2: Department of Biomedical Engineering; 3: Department of Anatomy and Neurobiology

Studies suggest that proprioceptive function determines the effectiveness of rehabilitative movement training after stroke (1-3). Here, we describe a design strategy for and initial experimental results with robots explicitly designed to assess and train proprioception, or “proprioceptive robots”. Based on a review of proprioceptive assessment methods, proprioceptive robots require two impedance states - rigid for guiding the user through passive movements and mechanically transparent for measuring active movements. We built proprioceptive robots for the fingers (PINKIE) and ankle (AMPD) that have binary impedance using clutched, backdriveable, mechanisms and rigid transmissions. To validate this approach we implemented the Crisscross test (2), for which PINKIE slowly moves the index and middle fingers or AMPD the ankle joints past each other in random patterns and the subject indicates when the joints are overlapped. Unimpaired subjects ($N = 8$) improved their finger or ankle proprioceptive acuity across 30 daily Crisscross assessments, demonstrating that repeated assessment with proprioceptive robots can serve as a somatosensory training technique. To increase the intensity of and motivation for proprioceptive training, we designed computer games based on a novel proprioceptive gaming paradigm that uses “propriopixels”. Instead of stimulating vision by conveying game dynamics through screen pixels, we stimulate somatosensation with propriopixels created by robotically driving the fingers and requiring players to continuously make game decisions based on sensed finger positions. For a group of 15 unimpaired subjects, playing 15 minutes of Proprioceptive Pong with propriopixels caused a significant reduction in Crisscross crossing error while playing visual Pong did not. These results show how somatosensation can be trained with proprioceptive robots that use propriopixels.

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TOPIC: Rehabilitation and assistive robotics

P-171

Combining Convolutional Neural Networks With LSTM for Real Time Decoding of Multi-Joint Arm Movements in Stroke Survivors

Jayashankar, Jayesh 1,2; Zhang, Li-Qun 2

1: University of Maryland, College Park, MD, USA; 2: University of Maryland, Baltimore, MD, USA and University of Maryland, College Park, MD, USA

Deep Neural Networks [1], [2] have been leveraged to decode multi-joint movements using surface electromyography (EMG) signals continuously and simultaneously with an emphasis on upper limb rehabilitation of stroke survivors. A major application is myoelectric control of exoskeleton robots in neurorehabilitation. This can be achieved if the deep learning model can make real time predictions of the subject's intended arm movements. Models such as linear-nonlinear cascade regression model [2] have been explored for real time decoding for a single muscle joint movement at a time. This study proposes a model combining Convolutional Neural Networks (CNN) with the Long Short-Term Memory (LSTM) model with the advantage that the convolution layers can extract high dimensional features and create informative representations of time series and the LSTM layers to learn long term dependencies as they are insensitive to time lags and the relevant information of the past states is maintained. Another advantage is that the input to the LSTM layers have convolutional structures and thus can maintain the time and space dimensions. The autoregressive and RMS features were extracted from the input EMG signals which were band pass filtered and differenced using a series of analysis windows. The cross validation was performed by splitting the data into 5 segments with 80% as the training set and the remaining 20% as the validation set. The decoding algorithm performed well for 10 stroke and 10 control subjects predicting accurately the three joints movements with the variance accounted for (VAF) being >95% for stroke subjects and >98% for the control subjects. Therefore, the proposed decoder model can potentially be employed in real-time myoelectric control of exoskeleton robots by estimating the multi joint movements of the human arm.

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This work was supported by: National Institute on Disability, Independent Living and Rehabilitation Research (NIDILRR)



Combining Convolutional Neural Network With LSTM for Real Time Decoding of Multi-Joint Arm Movements in Stroke Survivors

Jayesh Jayashankar and Li-Qun Zhang

University of Maryland School of Engineering, College Park and University of Maryland School of Medicine, Baltimore, USA



Introduction

Loss of motor control is common among neurologically impaired patients post stroke. Electromyography (EMG) signals can be leveraged by Deep Neural networks (DNN) to detect patient's intention and used to perform myoelectric control of exoskeleton robots. Previous systems either perform offline decoding or prediction of 1 DOF at a time. This study seeks to continuously and simultaneously estimate multi-joint movements of the shoulder, elbow and wrist from EMGs through a combination of Convolution Neural Networks and Long Short-Term Memory (LSTM) models. The advantage of combining two different models are that the long-term dependencies of high dimensional features can be extracted, and the time & space dimensions are maintained. The proposed decoder can be employed in real-time myoelectric control of exoskeleton robots.

Methodology

The subject moved the shoulder in horizontal adduction/abduction, and elbow and wrist in flexion/extension simultaneously back-and-forth through their ranges of motion. EMG signals of the anterior deltoid, posterior deltoid, biceps brachii, long head triceps brachii, flexor carpi radialis, and extensor carpi radialis muscles were recorded using surface electrodes and subsequently bandpass filtered with a 4th order Butterworth bandpass filter with cutoff frequencies of 20 and 400 Hz (Fig. 1).

The Neural Network was implemented in Python using the Google Colab framework. The filtered EMG signals were differenced to make the signals more stationary. The autoregressive model and RMS values were determined for each of the input EMG signals over a window of 1024ms wide and the window is shifted at an increment of 32ms. The architecture of the CNN LSTM model shown in Figure 2 comprises of 5 layers of CNN combined with 2 layers of LSTM. Inputs to the training model were the autoregressive and RMS features of the 6 channel EMG signals) extracted from the sliding 1024 ms side windows and the shoulder, elbow and wrist movement angles were the corresponding outputs.

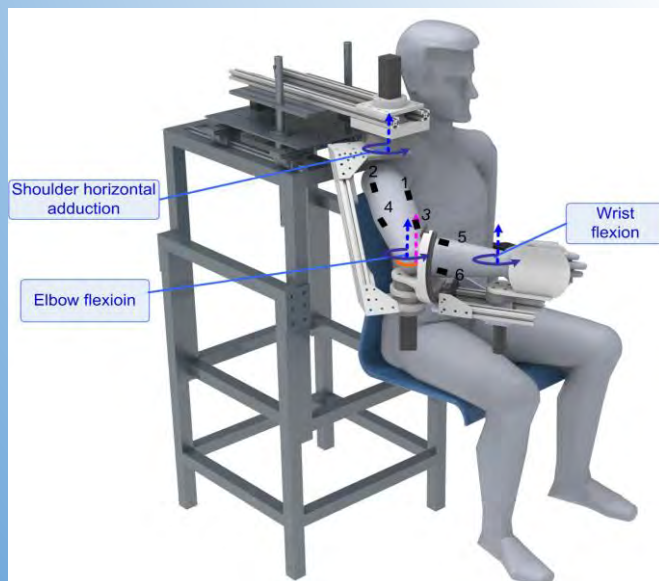


Figure 1: Experimental setup of the Shoulder, arm & wrist exoskeleton robot with multi muscle EMG measurements.

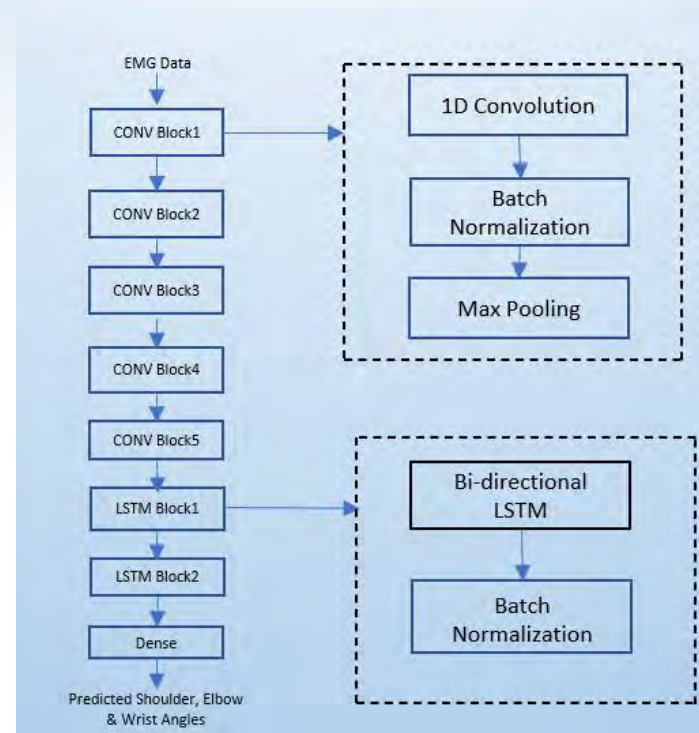


Figure 2: Architecture of the CNN-LSTM Network.

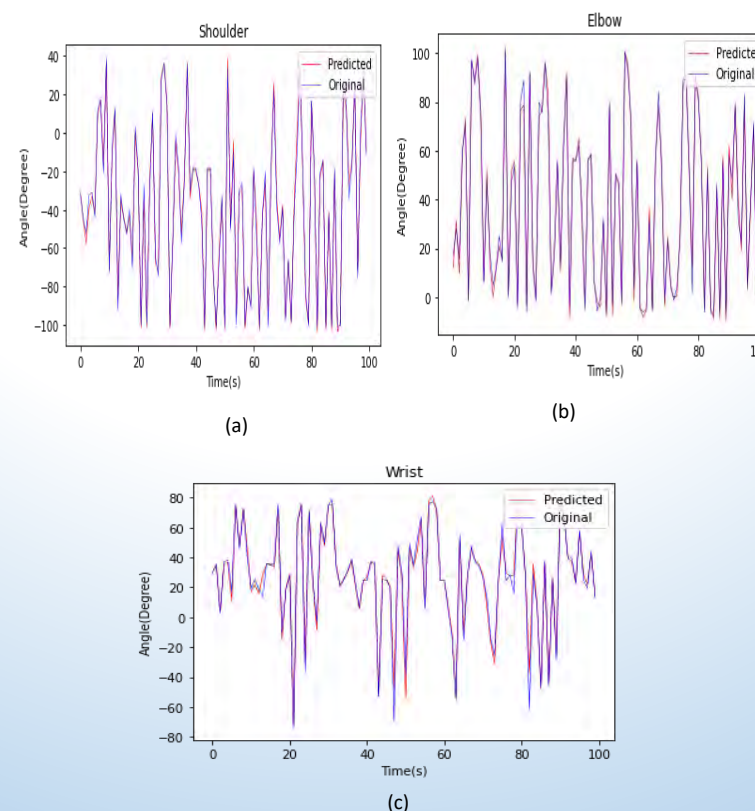


Figure 3. Decoded shoulder (a), elbow (b) and wrist (3) joint positions compared with the measured shoulder, elbow and wrist angles over the fresh validation set of data.

Results

The data were split into 5 segments with 80% as the training set and the remaining 20% as the validation set. The decoding algorithm performed well on 10 stroke survivors as well as 10 control subjects' data accurately in predicting the three joint movements with quantitative elements, including the average root mean square error (MSE) exhibiting a value at around 4 degrees for all the 3 joints and the average variance accounted for (VAF) being >95% for both groups of subjects (see Table 1). Therefore, the proposed decoder can potentially be employed in real-time myoelectric control of exoskeleton robots by estimating the multi joint movements of the human arm. The proposed method also outperforms other recent decoding algorithms such as Linear-nonlinear cascade regression model and the standalone LSTM model [2]. The NARX [1] is the only model which performs better but falls short when performing real-time decoding.

Table 1. VAF & RMSE for the shoulder, elbow and wrist averaged over 10 stroke and 10 control subjects

Joint	Shoulder	Elbow	Wrist
VAF (Control)	0.99 ± 0.01	0.98 ± 0.01	0.98 ± 0.01
VAF (Stroke)	0.97 ± 0.01	0.95 ± 0.02	0.95 ± 0.01
RMSE (Control)	4.44 ± 0.71	4.96 ± 0.53	4.92 ± 0.67
RMSE (Stroke)	5.13 ± 0.32	4.47 ± 0.82	3.63 ± 0.91

Discussions & Conclusion

The CNN LSTM model can predict a set of joint angles in about 7 microseconds thus making it suitable for real-time continuous and simultaneous decoding.

Future work on the usage of this model involve:

- 1) Using the predicted joint angles to perform myoelectric control of an exoskeleton robot for upper limb rehabilitation of stroke survivors.
- 2) To evaluate how specific muscle groups contribute to the Joint displacements by evaluating relationship of the EMG signals and the predicted joint outputs.
- 3) To analyze why the performance of the decoder falls short for some stroke survivors as the EMG signals of for an impaired limb might be non-existent and changed substantially.

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Disclosure

Zhang has an equity position in Rehabtek LLC, which received U.S. federal funding in developing the rehabilitation robot used in this study.

REHAB WEEK 2021

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VIRTUAL EVENT



TOPIC: Human-machine interfaces in rehabilitation

P-172

Prediction of Fingertip Force and Joint Kinematics of Individual Fingers using Motoneuron Firing Activities

Roy, Rinku 1; Xu, Feng 1; Kamper, Derek 1; Hu, Xiaogang 1

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University of North Carolina-Chapel Hill and NC State University, Chapel Hill, NC 27599 USA

Objective: Advanced assistive robotic hands can help individuals with hand impairment to perform daily activities. The detection of intended motor output of individual fingers, however, remains a challenge. Fingertip forces or joint angles can be predicted from myoelectric signals in separate studies. However, our daily activities consist of both isometric and dynamic tasks. Therefore, it is important to concurrently predict kinematic and kinetic variables related to an individual finger, in order to effectively operate assistive devices. Here, we used populational motoneuron firing frequency to continuously and simultaneously predict fingertip forces and joint kinematics of individual fingers. **Methods:** High-density electromyogram (HD-EMG) signals were recorded while healthy participants performed isometric and dynamic finger movement tasks with index and middle fingers. A blind source separation method was applied to EMG signals to obtain motor unit (MU) firing activities. An MU refinement procedure was then used to determine finger- and task-specific MU pools. The obtained MU pool information was tested on a different dataset involving both isometric and dynamic tasks. Populational MU firing frequencies were then calculated to estimate the fingertip forces and joint angles concurrently using regression models. Model performance was compared to a conventional EMG amplitude-based approach. **Results:** The MU approach led to better performance (a higher correlation between the predicted and measured output and a lower prediction error) in predicting both joint angles and fingertip forces than the EMG amplitude approach. **Significance:** Our MU firing frequency-based approach can successfully identify MU pools for a specific task involving individual fingers, allowing dexterous control of fingertip forces and joint angles concurrently with assistive robotic hands. As refined MU pools were directly applied to a new set of tasks, the approach can also be used for real-time.

REHAB WEEK 2021

23-25 SEPTEMBER 2021
VIRTUAL EVENT



TOPIC: Rehabilitation and assistive robotics

P-173

Exploring the efficacy of cutaneous haptic feedback in post-stroke rehabilitation

Khan, Mohid 1; George, Teresa 1; Carducci, Jacob 1; Ma, Timothy 2; Krakauer, John 3; Xu, Jing 4; Brown, Jeremy 1

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Stroke is a leading cause of long-term disability in individuals 65 and older, restricting them from completing activities of daily living. Considerable research has shown that hand strength and dexterity are dissociable behaviorally and biologically, and that targeted rehabilitation for dexterity is needed for a fully functioning hand. It is, however, not clear what is the role of sensory feedback in the recovery of dexterity. Here, we present a novel hand dexterity rehabilitation device that focuses on the finger sensory feedback. The device measures forces at the fingertips and converts them into visual haptic cues. Our work complements the work of Chiu et al., who used a Novint Falcon to simulate a pinch-task. Utilizing a portable hand rehabilitation device with force sensors embedded under the flexible retention cups, we can measure 3D isometric forces produced at all five fingertips. The raw force data is converted into visual-haptic cues with a custom DAQ board.

The hardware and software interface of the device can assess a variety of hand behaviors. For example, one task is a precision pinch task, in which the user controls dots representing forces exerted at fingertips and attempts to grasp a virtual ball. At the beginning of the trial, all dots representing irrelevant task fingers disappear. The user must then engage the instructed fingers in a pinching motion until they touch the gray ball, which changes its color to blue and disappears.

In addition to visual feedback, vibrotactile haptic feedback is provided by eccentric rotating mass motors placed near the interphalangeal joint of each finger. The feedback is proportionally mapped to the location of the user's fingers, represented by the virtual dots in the task. As the virtual dots get closer to the gray ball, the vibration intensity increases. We are currently preparing to evaluate the system with healthy participants before assessing the efficacy of the haptic feedback system in stroke patients.

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REHAB WEEK 2021

23-25 SEPTEMBER 2021
VIRTUAL EVENT



TOPIC: Rehabilitation and assistive robotics

P-174

Novel end-effector device for patient-in-charge model-based progressive gait rehabilitation

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INTRODUCTION

Stroke survivors exhibit a variable motor deficit whose recovery can be pursued through physical exercises eliciting brain plasticity [1]. In particular, researchers agree that improvement is a result of patient's attempt at exerting correct neural control of muscle effort.

Therefore, robot intervention should allow volitional activity and give a performance-based feedback in order to foster user's engagement, while enabling the user to complete the task by providing assistance as needed.

Our aim was to implement a footplates-based gait rehabilitation device which:

- Interacts with the user who is empowered to direct the motion.
- Allows to reduce task level and assigns a progressive exercise, based on an impairment model which incorporates recently developed theory of gait modularity.

MATERIAL AND METHODS

- Prototype description

A prototype has been built in the robotic lab of the University of Birmingham. The footplates can move along a linear guide up to 2 [m/s], actuated by a DC gearmotor via a belt transmission. The foot connection allows metatarso-phalangeal joint motion in the vertical direction.

- Control system for virtual floor rendering

Body Centre of Mass (CoM) position is estimated using an observer that fuses data from horizontal and vertical ground reaction forces (GRF).

When one or both feet are in stance phase (virtual floor contact) footplates motion in the antero-posterior direction is driven by CoM position, so that the user can increase speed by applying greater force.

- Model-based task reduction

Gait cycle modules contribute to CoM support and progression [2] (fig. 1), but user's impairment can reduce her/his capability to recruit such modules with resulting unfitness to properly complete the gait cycle [3].

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The control system of the prototype gives the possibility to the user to complete the gait cycle whenever in some parts of the stance phase the limb is not able to support 100% of the body mass.

References: Schaechter, Judith D. "Motor rehabilitation and brain plasticity after hemiparetic stroke." *Progress in neurobiology* 73.1 (2004): 61-72., Ting, Lena H., et al. "Neuromechanical principles underlying movement modularity and their implications for rehabilitation." *Neuron* 86.1 (2015): 38-54, Cheung, Vincent CK, et al. "Muscle synergy patterns as physiological markers of motor cortical damage." *Proceedings of the national academy of sciences* 109.36 (2012): 14652-14656

Novel end-effector device for patient-in-charge model-based progressive gait rehabilitation

Marco Maddalena and Mozafar Saadat
School of Engineering, University of Birmingham, UK

Introduction

Stroke survivors exhibit a variable motor deficit whose recovery can be pursued through physical exercises eliciting brain plasticity [1]. In particular, researchers agree that improvement is a result of patient's attempt at exerting correct neural control of muscle effort. Therefore, robot intervention should allow volitional activity and give a performance-based feedback in order to foster user's engagement, while enabling the user to complete the task by providing assistance as needed.

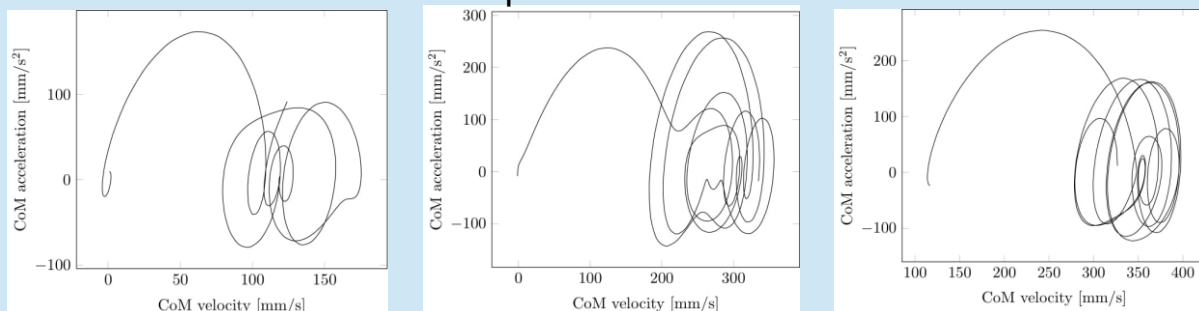
Our aim was to implement a footplates-based gait rehabilitation device which:

- Interacts with the user who is empowered to direct the motion.
- Allows to reduce task level and assigns a progressive exercise, based on an impairment model which incorporates recently developed theory of gait modularity.

Results

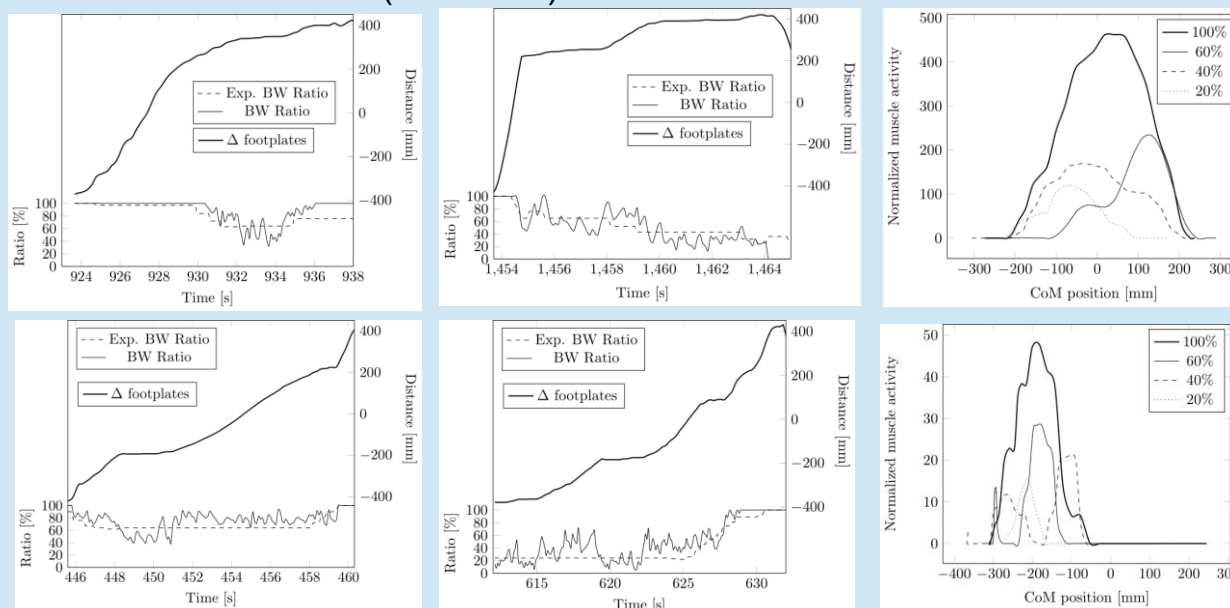
A healthy volunteer has been involved for carrying out some tests on interaction with the device.

To test patient-in-charge function, the volunteer was asked to reach a steady speed while walking in the device. The phase portraits below show the result for different speeds.



Progressive task reduction was simulated for module 1 (first row of figures) and 4 (second row) as the user was asked to apply least force possible to complete the gait cycle.

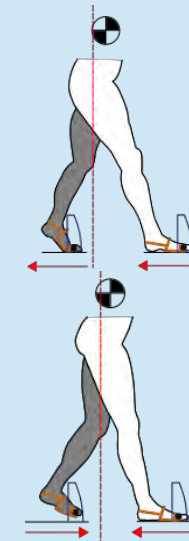
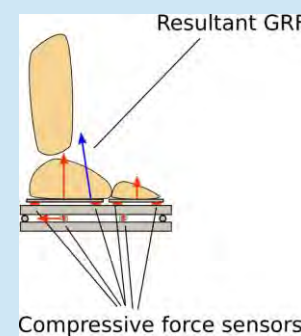
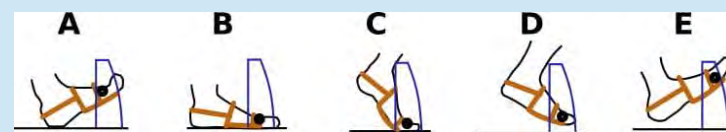
60% and 20% module activation limits allow the user to exert a progressively smaller effort (supported body weight ratio) to complete the gait cycle, whether in initial or in final part depending on the module. Last column shows the corresponding reduction in Electro Myography (EMG) activity of Gastrocnemius Medialis (contributing to module 1) and Rectus Femoris (module 4).



Materials and Methods

Prototype description

The prototype features two footplates actuated along a linear guide, while the foot connection allows the user's metatarsophalangeal (MTP) joint motion in the vertical direction while simulating walking.



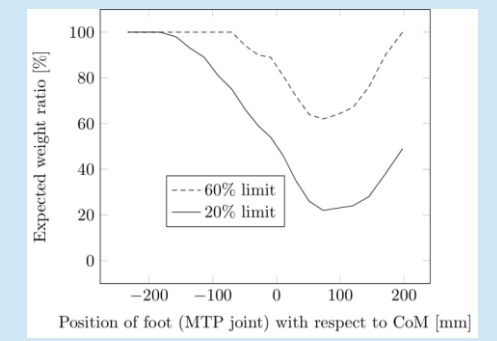
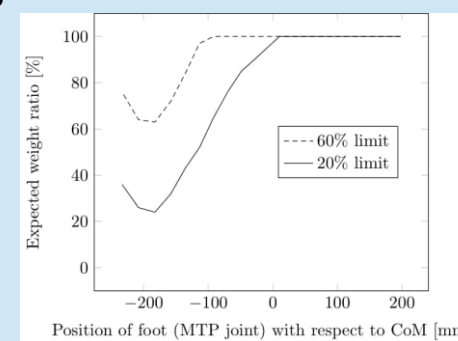
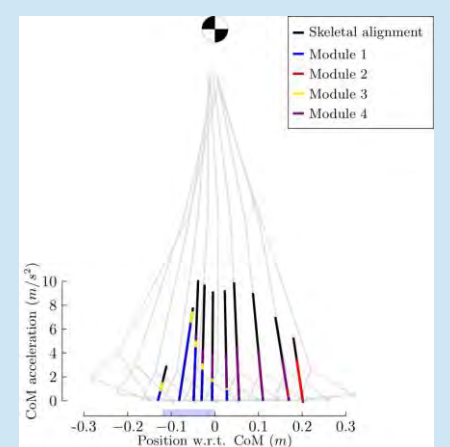
Control system for virtual floor rendering

User's body Centre of Mass (CoM) advancement makes the actuation system to move footplates backward to render virtual floor. Lifting the weight from the foot enables the transition to swing phase, bringing that foot forward. CoM position is estimated using an observer that fuses data from horizontal and vertical ground reaction forces (GRF).

Model-based task reduction

Muscle activation primitives (modules) can be used to model the user's impairment level in terms of vertical force which can be applied to support the CoM [2,3].

The device control system adapts to impairment allowing the user to complete the gait cycle even if the user is applying only a rate of total body weight. Different modules corresponds to different parts of the gait cycle (below, left: module 1; right: module 4), while decreasing level of module activation limit corresponds to decreasing level of expected weight ratio.



Conclusions

The developed device presents promising features for tackling post-stroke gait rehabilitation. It allows the user to lead the motion of the footplates, implementing the principle of patient-in-charge therapy, while task can be progressively scaled down so as to enable the user to complete the gait cycle employing reduced muscle activity.

Future work will comprise further testing involving a higher number of unimpaired subjects and affected individuals.

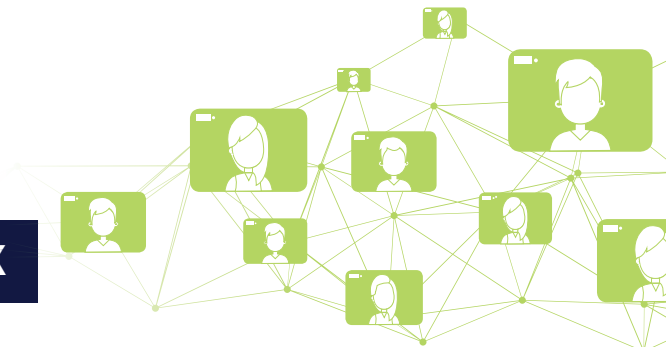
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ABSTRACT E-BOOK



EVOKED SENSATIONS WITH SINUSOIDAL TRANSCUTANEOUS ELECTRICAL STIMULATION AT DIFFERENT FREQUENCIES

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Abstract: *Afferent nerve fibres associated to the somatosensory system can be excited by means of transcutaneous electrical stimulation. Current Perception Threshold (CPT) is a technique that applies current sine waves through the skin at 2KHz, 250Hz and 5Hz to excite A β , A δ , and C fibres correspondingly. CPT has been successfully applied to detect sensitivity abnormalities and diagnose some pathologies such as diabetic neuropathy. The ability of the mentioned frequencies to preferentially excite different nerve fibre types and the normative sensory thresholds associated to them have been already established in literature. However, the sensation evoked by the stimuli targeting different afferent fibres types has not been studied yet. In this pilot study, the sensation evoked by these frequencies is analysed in 10 healthy volunteers. A qualitative analysis of descriptors including perceived sensation modality, localization, intensity and emotion, shows that it is possible to evoke different sensations by preferentially exciting different types of fibres.*

Keywords: *electrical stimulation, selectivity, afferent stimulation, sensation, CPT*

Introduction

All afferent nerve fibres associated to the cutaneous mechanoreceptors can be classified as either A β , A δ , and C fibre types based on their axon diameter, myelination and conduction velocities. Amyelinated C fibres transmit noxious mechanical or thermal stimuli with a long delay. Thinly myelinated A δ fibres also transmit noxious stimuli but at higher velocities, whereas, thick myelinated A β fibres are mainly responsible for transmitting tactile information [1]. Applying current sine waves through the skin at different frequencies (2000, 250 and 5 Hz), has shown the ability to specifically excite each of these three types of fibres [2-4]. One study demonstrated that the 2000 Hz sine wave preferentially activated A β fibres at low intensity, and that higher intensities produced action potentials in A δ fibres. Stimulation at 250 Hz initiated both nociceptive sensation through the A δ fibres and tactile sensation through the A β fibres. Finally, the C-fibres were only activated at 5 Hz. Although the A δ and A β fibres were also activated at 5 Hz, they did not reach a frequency enough to induce functional sensation [5]. Another study confirmed these results, showing that the sine waveform at 5 Hz preferentially stimulated C-type fibres [6].

This ability of the sinusoidal waveform to preferentially stimulate different nerve fibres has been incorporated in a technique called Current Perception Threshold (CPT) for evaluating the function of the sensory fibres, which has

been successfully applied to diagnose neuropathic diabetes [7-9]. Painless normative CPT thresholds have been established recently in the literature for various cutaneous and/or mucosal sites of the body and the correlation of these thresholds with stimulation frequency, sex, age, and body fat has been demonstrated [10-12].

Although the capacity of preferentially exciting different nerve fibres of the sinusoidal waveform has been established, to the best of authors knowledge, to date the sensation evoked by the different frequencies has not been studied or reported yet. This type of stimulation could be used for evoking different sensations by means of transcutaneous electrical stimulation, which could be useful for medical and other types of applications. This pilot study analyses the sensation evoked by the sinusoidal waveform at the frequencies that have shown to preferentially excite different nerve fibres (5Hz, 250Hz and 2KHz) in 10 healthy subjects.

Methods

The electrical waveforms were generated by a commercial low-voltage high-accuracy AC and DC current source (Keithley - Model 6221), which was controlled by means of an Ethernet connection from a PC. A sinusoidal waveform at three different frequencies was applied: 5Hz, 250Hz and 2KHz.

The electrodes used in this study were 25mm-diameter commercial self-adhesive electrodes (TensCare Ltd.), which were adapted to mimic the dimensions of the CPT cup electrodes. For this, an insulation layer was added under the conductive gel, so that only the central core of 10mm diameter of each electrode was allowed to conduct and 17mm distance was left between the electrodes.

In order to collect qualitative information about the sensory perception, the custom-designed descriptor form shown in Table I was used, where the participant marked with an "X" the descriptors that best described his/her sensation. This form was designed based on sensory and emotional scales of touch perception [13,14], pain quality scales such as the Revised Short-Form McGill Questionnaire [15] and the Pain Quality Assessment Scale [16], and other studies that analysed the sensations caused by transcutaneous electrical stimulation [17,18].

This pilot study was approved by the local Ethics Committee of Osakidetza (Comité Ético de Investigación Clínica OSI Ezkerraldea-Enkarterri-Cruces), part of the Public Basque Health System. It was carried out with 10

volunteers without any type of sensory or cognitive disability that signed an informed consent. The sessions of approximately one hour of duration took place in the Tecnalia labs. The set up consisted in a chair where the participants remained seated with the researcher controls out of their visual range. The electrodes were placed aligned along the axis of the extensor tendon of the index finger, with the distal electrode over the middle of the second metacarpal.

Electrical stimuli of different frequencies and different amplitudes (0.05mA resolution) and 2 seconds of duration were applied randomly to the participants in an automatic manner, while the participant verbally indicated the perception of a stimulus. The sensory threshold for each of the three frequencies was then set as the lowest amplitude perceived by the participant and above which all the stimuli have been perceived.

After the sensory thresholds were defined, a stimulus of 5 seconds of duration was applied with an amplitude 50% higher than the sensory threshold for the three frequencies. The participant was then instructed to mark the qualitative descriptors (Tab. 1) that best described the evoked sensation for each of the three stimuli.

Table 1: Perception descriptors.

Modality	Localization	Intensity	Emotion
Touch	Localized	Low	Uncomfortable
Vibration	Radiating	Medium	Comfortable
Heat	Referred	High	Exciting
Cold			Irritating
Tingle			Pleasurable
Itch			Relaxing
Prickle			Painful
Pinch			Neutral
Pressure			
Movement			
Numbness			

Fisher's exact test with Bonferroni's correction was applied to the results to check if there were statistically significant differences between the different frequencies and the perception modality, localization, intensity and emotion descriptors.

Results

The sensory thresholds, presented in Tab. 2, are in line with data from literature [10-12], where sensory thresholds show an ascending trend that is proportional to the applied frequencies.

Regarding the perceived sensations, Fig. 1 shows the large heterogeneity in terms of sensation modalities referred by the participants. No statistical differences were found between the different frequencies. However, we can observe that stimuli at 250Hz and 2KHz produced a tingling sensation in 7 subjects but only in 3 subjects at 5Hz. On the other hand, prickling sensation was felt by 5 subjects at 5Hz, but only by 1 subject at 250Hz and none at 2KHz.

Table 2: Sensory thresholds.

Frequency (Hz)	Mean (mA)	SD (mA)
5	0.35	0.091
250	0.63	0.151
2000	1.905	0.727

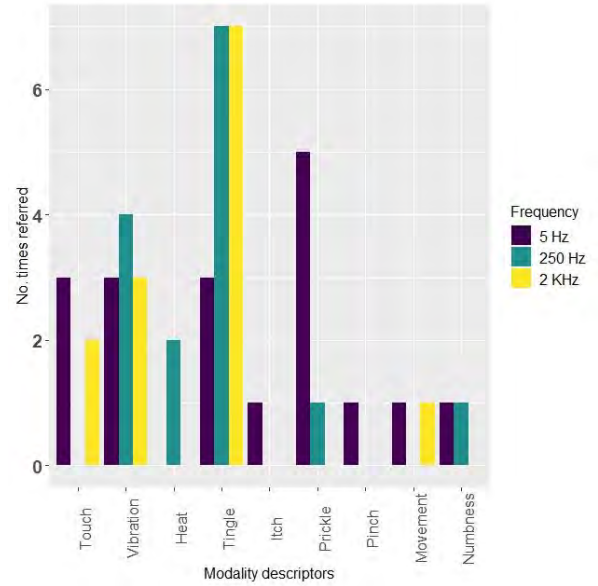


Figure 1: Perceived sensation modality for stimuli with different frequencies.

In Fig. 2 we can observe that participants did not feel the electrical stimuli referred in other body locations for any frequency. Although the statistical analysis did not show significant differences between the three groups, more participants felt a localized sensation as the frequency of the stimuli increased. In the case of 5Hz half of the participants felt the stimuli as radiating and half as localized, whereas in the case of 2KHz, 8 participants felt the stimuli as localized and only 2 of them felt a radiating sensation. Nobody reported a referred sensation and all participants that felt a radiating sensation expressed that they felt the stimulus radiating from the dorsum of the hand towards the fingers.

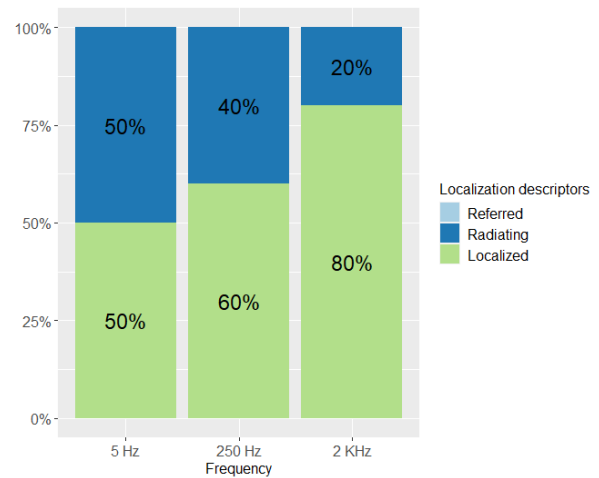


Figure 2: Perceived localization for stimuli with different frequencies.

The perceived intensity for the stimuli at different frequencies is shown in Fig. 3. In this case, a peculiar behaviour is observed, as lowest and highest frequencies seemed to be perceived as lower intensities than middle frequencies. Actually, 7 and 8 participants perceived low intensity stimuli for 5Hz and 2KHz respectively. On the other hand, 7 subjects perceived a medium intensity sensation when a 250Hz stimulus was applied and only 2 subjects perceived the stimulus as low intensity. One participant felt the stimuli at both 250Hz and 2KHz frequencies as high intensity. In this case, the Fisher's test showed a significant reduction ($p=0.006$) of low intensity perceived stimuli and a significant increase ($p=0.012$) of medium intensity perceived stimuli at 250Hz compared with the rest of frequencies.

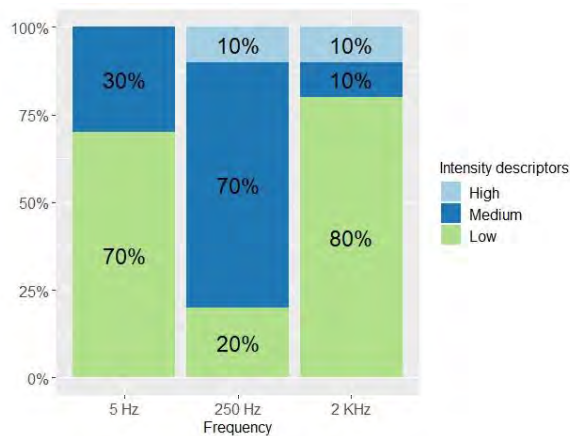


Figure 3: Perceived intensity for stimuli with different frequencies.

Finally, Fig. 4 shows the perceived emotions related to the stimuli at different frequencies. Although no significant differences between groups were found in this case either, Fig. 4 shows slightly less heterogeneity than Fig. 1, as we can clearly see that all participants reported positive or neutral emotions for 2KHz stimuli, but not for the other frequencies. No stimulus was found painful or exciting by any participant.

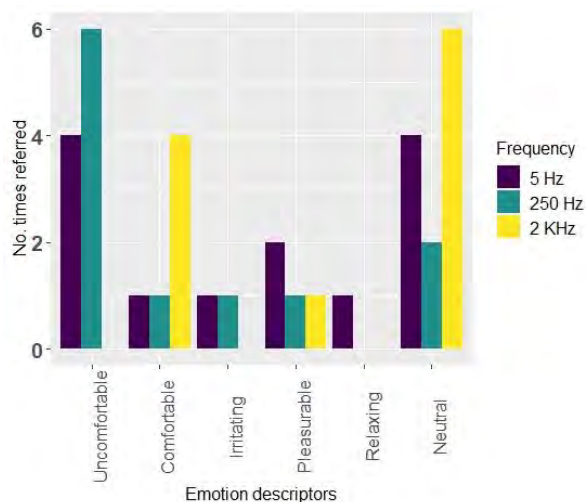


Figure 4: Perceived emotion for stimuli with different frequencies.

All participants perceived the stimuli as neutral, comfortable or even pleasurable at 2KHz. However, 6 and 4 subjects reported an uncomfortable sensation for 250Hz and 5Hz respectively, and 1 subject even perceived the stimuli as irritating for these both frequencies.

Discussion

The results of this study may suggest that sinusoidal transcutaneous electrical stimulation at different frequencies might evoke different sensations due to preferential activation of different afferent fibres as stated in literature. At 5Hz mostly a localized or radiating prickling sensation was perceived by the participants, which was described as neutral or uncomfortable even at low intensities. 5Hz stimuli excite C-type fibres, which are assumed to carry mainly noxious information to the brain, so even if no painful sensation was reported, this can explain the uncomfortable prickling sensation described by most of the participants. Regarding 250Hz stimuli, they excite mostly A δ fibres, which also carry noxious and thermal information, but as amplitudes are increased also A β fibres are recruited [5], which carry information related to touch. This could be the reason why a mostly localized moderate tingling sensation was perceived by the participants, who reported the feeling mostly as uncomfortable. Finally, the 2KHz frequency preferentially excites A β fibres, which may explain why it produced a localized, low intensity, comfortable tingling sensation in most participants, because no nociceptors were recruited.

It should be mentioned, that although these findings support the results from other previous studies, the sample size was limited and perhaps this was the reason why no statistical differences were found in most cases. This study should be carried out with a bigger sample size to confirm the results and a deeper analysis should be carried out to understand why no painful or thermal sensations were evoked when supposedly C and A δ fibres were excited. Similarly, the reason behind the higher intensity perceived by the participants when 250Hz stimuli were applied compared to 5Hz and 2KHz should also be investigated.

Acknowledgement

This research was supported by grants of the Basque Government through the EXAMINA project (KK-2019/00047).

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IMU triggered FES for Robotic Gait Training

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Abstract: A concept combining functional electrical stimulation with robotic gait training using linear acceleration and angular velocity data from inertial measurement units was evaluated towards its performance. The performance was determined by means of latency measurements. Each element of the execution chain of the developed concept was evaluated individually, furthermore aspects such as, stimulator delay, electromechanical delay, and Bluetooth transmission (measurement chain) were investigated to get a holistic view on the feasibility and applicability of the concept. The delay of the gait recognition algorithm was $282\mu\text{s} \pm 17\mu\text{s}$. The trigger instant for FES induced a mean latency of $1.74\mu\text{s} \pm 0.58\mu\text{s}$. Investigations towards the electromechanical delay showed a delay of 100ms, Bluetooth transmission induces a latency below 46ms. The internal delay of the stimulator is 2ms. The overall concept including all relevant components thus induces a delay of 148.282ms. Based on the acquired results, the proposed concept to use IMUs to trigger FES during robotic gait training provides promising results for the further development of a hybrid robotic rehabilitation system.

Keywords: IMU, FES, hybrid robotic rehabilitation systems

Introduction

Gait disorders caused by neurological defects such as stroke are two major problems in the daily life of the affected people [1, 2]. In clinical routine, conventional rehabilitation techniques such as physiotherapy and device-based techniques such as robotic gait training and functional electrical stimulation (FES) are used to support the rehabilitation process. Two consecutive reviews have shown that robotic gait training in combination with conventional therapy has the potential to be more effective in regaining independent walking compared to solely conventional therapy [3, 4]. FES as a therapy modality has shown to improve aspects of daily activity performance [5], furthermore FES promotes upper and lower extremity functions [6–13]. The combination of the two device-based techniques can be termed “hybrid robotic rehabilitation system” and has shown to be more effective than robotic gait training alone [14]. Approaches to develop hybrid robotic rehabilitation system are promising and some systems are commercially available. However, so far, most of the developed systems rely on data provided by the robotic system or rely on human interaction [15–22] limiting the approaches to specific gait trainers or are subject to human error. A previously developed concept (Figure 1) uses linear acceleration and angular velocity data from inertial

measurement units (IMUs) attached to the subjects’ lower limbs to collect movement data and extract gait events during robotic gait training. The extracted gait events can perspective be used as a trigger instant for FES. The approach has shown to be feasible with healthy subjects [23] and robust for the application during clinical routine with stroke patients [24]. Yet so far, the approach has only been investigated towards the capability of gait recognition during robotic training and not towards the capability of triggering FES in real-time. Thus, the performance of the proposed concept was investigated within this research.

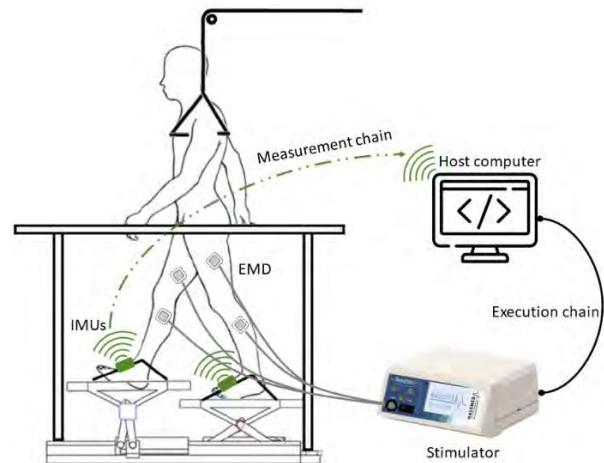


Figure 1: IMU triggered FES for Robotic Gait Training

Methods

The performance of the developed concept was evaluated by means of analysing the induced latency of the measurement and execution chain. The resulting latencies describe the induced delays between input and output samples of the corresponding element of the algorithm. Thus, the overall latency reflects the computation time of the algorithm. The latency is independent of whether the input data is a robot-induced gait pattern or human walking. It solely defines the computation time of the implemented algorithmic sequences and does not evaluate the detection accuracy, limitations or boundary conditions of the approach published in [23, 24]. For the analysis a total amount of 60,000 samples (overground walking dataset of a 29-year-old healthy adult) corresponding to 120 seconds at a sampling frequency of 500 Hz were evaluated. For data recording, the inertial measurement unit MotionSensor (HASOMED GmbH, Magdeburg, Germany) was used. The stimulation device RehaStim (HASOMED GmbH, Magdeburg, Germany) with the communication protocol ScienceMode was

utilized to implement the stimulation algorithm. For the latency measurements, the surface electrodes were replaced by custom-made LEDs which represent the electrodes and ensure the functionality of the concept during bench-testing. The latency of pre-processing and the individual elements of the gait recognition algorithm were measured using the MATLAB stopwatch-timer (tic/toc;). The tic-event was activated by each sample that entered the algorithmic element. After processing the sample, the toc-event was utilized to measure the elapsed processing time. The mathematical description of the algorithm including the pre-processing, which refers to an arbitrary sensor alignment algorithm, is described in detail in [23] and [24]. Additionally, the latency of the FES trigger instants and the overall latency of the algorithm were measured using the same method. Furthermore, the resolution of the stopwatch-timer was considered. As a host-computer a LENOVO ThinkPad E590 with an Intel Core i7, Windows 10 and 8GB of working memory was used.

In Figure 2 the flowchart of the measurement process is visualized. The latency measurement for each part was repeated ten times; mean, and standard deviation were calculated for each element.

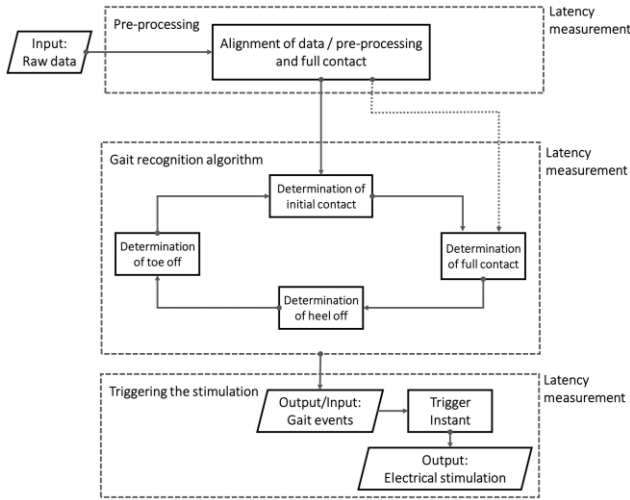


Figure 2: Flowchart: Latency measurement of the execution chain

In addition to the measurements of the latency of the execution chain, the measurement chain realised by a Bluetooth connection between the IMUs and the host-computer, and the electromechanical delay (EMD) of the muscles were considered in order to holistically analyse the developed concept.

Results

The presented results reflect the latency induced by one IMU. As each IMU is processed independently from each other, the same analysing concept can be assumed for further sensors. In Table 1, the latency of the pre-processing and the gait recognition is shown. The result of the overall latency of the algorithm describes the induced delay from pre-processing including the gait recognition algorithm. Pre-processing including full contact induced a latency of

$244\mu\text{s} \pm 13\mu\text{s}$. The individual gait recognition elements each caused a delay below $17\mu\text{s}$. The overall latency of the algorithm for one IMU was $282\mu\text{s} \pm 17\mu\text{s}$. The resolution of the stopwatch-timer function was $5\mu\text{s} \pm 0.1\mu\text{s}$.

Element of algorithm	Mean (μs)	SD (μs)
Pre-processing and full contact	244	13
Initial contact	3	0.2
Heel off	4	0.2
Toe off	16	5
Overall algorithm	282	17
Resolution (tic/toc)	0.5	0.1

Table 1: Latency: Pre-processing and gait recognition

For the trigger instants the induced latencies of the communication commands from the ScienceMode were measured. Therefore, each update command (trigger instant) from the ScienceMode protocol was measured individually, the results are display in Table 2.

Trigger instant	Mean (μs)	SD (μs)
Initial contact	1.79	0.64
Full contact	1.69	0.61
Heel off	1.74	0.49
Toe off	1.72	0.58

Table 2: Latency: FES trigger instants

The mean latency over all trigger instants was $1.74\mu\text{s} \pm 0.58\mu\text{s}$.

Taking additional aspects such as measurement chain, EMD and the internal delay of the stimulator into account, an overall delay of the concept as shown in Table 3 can be derived. The latency of the measurement chain is based on the delay of a Bluetooth communication [25] and has been reported to be below 46ms. The EMD is highly dependent on the subjects fitness, gender, age, muscle condition and various other factors [26–29]. Investigations towards lower limbs of male subjects showed EMDs between 97ms and 110ms, other experimental studies showed EMDs between 8ms and more than 100ms [30–32]. Taking the mentioned data into account, a EMD of 100ms was chosen for further evaluation of the concept.

Component	Approx. latency (ms)
Measurement chain	46
Execution chain	0.28
Trigger instant	0.002
Stimulator	2
EMD	100
Overall concept	148.282

Table 3: Latency: Overall concept

As a result of the measurements and the investigations towards other aspects of latency, an overall latency of approx. 148.282ms can be derived for the concept. Whereas the physiologically induced delay has the highest contribution (67.4%) to the overall latency.

Discussion

The feasibility and applicability of FES supported therapy during movement training is based on the capability of triggering the stimulation within a certain time window to support the movement with electrical stimulation. For robotic gait training, a feasible stimulation should be generated prior to loading 50% of the body weight onto the stance leg to ensure that the stance muscles are activated accordingly [15]. For healthy adults this weight shift occurs after 5% of the gait cycle starting from the initial contact [33].

As a result, the developed concept (Figure 1) must provide a trigger instant which is fast enough to stimulate the stance muscles within this certain period. Considering the overall delay of the concept including the physiological process of EMD (148.282ms) and taking into account that the stimulation of the muscle must happen at 5% of the gait cycle to support the stance period, a time of 2965.64ms would be the shortest feasible step duration during robotic training. As a result, further investigations towards the importance of EMD with respect to FES in robotic gait therapy should be conducted. Furthermore, in future works the step time of subjects during robotic gait therapy should be investigated in order to evaluate the applicability of the concept during clinical routine. In addition, the performance depends on the detection accuracy of the approach, thus investigations with gold standards should be conducted to further evaluate the proposed concept.

In conclusion, the developed setup provides promising results for future research on a concept which can support robotic gait therapy with functional electrical stimulation. Moreover, the developed concept can be optimised in terms of latency and size by integrating the execution chain (pre-processing, gait recognition and trigger instants) into an embedded device that incorporates all relevant functionalities for a hybrid robotic rehabilitation system.

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FEASIBILITY OF A BIMANUAL BCI-FES SYSTEM IN STROKE

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Abstract: Brain computer interface actuated functional electrical stimulation (BCI-FES) is an emerging neurorehabilitation approach post-stroke. Most BCI-FES systems focus on the affected hand only. We explored the feasibility of a bimanual BCI-FES system and compared it to a unimanual BCI-FES system. Ten people with subacute stroke and ten age-matched controls participated in two sessions of BCI-FES, using unimanual and bimanual movements, respectively. Event related desynchronization (ERD) was derived from movement data. Both groups were able to control the bimanual BCI-FES system with similar activation rates. Both groups showed predominantly contralateral ERD for unimanual movements and bilateral ERD for bimanual movements. A bimanual BCI-FES control offers a larger repertoire of movements and does not suppress ERD of the affected side.

Keywords: Stroke, BCI-FES, bimanual, ERD

Introduction

Stroke is the leading cause of long-term disability causing a reduced quality of life and increased socioeconomic burden to society. Despite the rigorous rehabilitation after stroke, the outcomes are still limited. Brain computer interfaces (BCI) are devices that can use movement imagination or attempts related brain signals, typically measured by an electroencephalogram (EEG) to control an external device like wheelchair, cursor, orthosis, or functional electrical stimulation (FES). BCIs are increasingly being used for neurorehabilitation after stroke [1]. Brain patterns in movement imagination or attempts based BCI are based on the changes in sensorimotor rhythms (SMR), alpha (8-12 Hz) and beta (12-30 Hz). This change involves movement induced decrease in SMR power, called event related desynchronisation [2]. In healthy individuals, most functional activities are accomplished using both hands but the performance of these activities deteriorate and bilateral arm use is reduced post-stroke [3]. Despite this, most BCI-FES therapies for stroke target rehabilitation of the affected hand only. However, it has been found bilateral priming is as effective as unimanual training [4]. There are however no studies comparing the EEG measured brain activity between BCI-assisted unimanual and bimanual training. In this study, we test the feasibility of a bimanual BCI-FES system and compare it to an unimanual BCI-FES system.

We also compare the parameters between people with stroke and healthy controls.

Methods

Ten people with subacute ischemic stroke (mean \pm std age 60.2 ± 10.4 , Fugl Motor Assessment UA score 14-60, Mini mental state exam. 25-30) participated in this study, 3 with left lesion in left brain and 7 with lesion in right brain. Ten right-handed healthy controls (mean \pm std age 59.6 ± 2.4) participated in the study. All participants gave Informed consent.

EEG data was recorded from C3 and C4 and FES electrodes were placed over the forearm extensor muscles. There were two sessions of BCI-FES: unimanual (UNI) and bimanual (BI). The stroke (ST) group used the affected hand, which was the left hand in 7 participants. The control (CO) group matched the ST group. Each session consisted of a calibration stage and a BCI control stage. The calibration involved 2 runs, each involving 10 repetitions of rest followed by attempted/executed movement with action observation (AM/ME-AO). The BCI control stage involved 3 runs of 10 trials each. Within one trial, the user was cued to attempt/execute UNI movement in UNI session, and BI movement in BI session. They had minimum of 1 s and maximum 10 s to activate the FES. Successful trials were followed by a 5 s FES.

The two parameters used for UNI BCI control: threshold and frequency band were obtained from the calibration data. The band within 8-30 Hz with maximum event related desynchronization (ERD) or movement (AM/ME-AO) related decrease in power was selected [5] with threshold being the power in that band. The online data was epoched into overlapping windows and power was evaluated in the selected frequency band. The BCI-FES control was based on a time-controlled threshold switch [6], where power has to be below a percentage of threshold for a certain time for FES to be triggered. For UNI session, real-time contralateral power had to be below threshold while for BI session, both C3 and C4 powers had to be below their respective thresholds simultaneously.

The activation rate was calculated by expressing the number of successful trials as a % of total trials. The baseline-normalised event related spectral perturbations (ERSP) o

changes in power were obtained and averaged over selected frequency band. ERD during AM/ME was derived by summing ERSP values over 2 s of AM before FES activation. Positive values were set to 0. Wilcoxon sign-rank and rank-sum tests were used to compare data within and between groups, respectively at a significance level of 0.05.

Results

The UNI mean \pm std activation rates for ST and CO groups were 78.7 ± 12.4 % and 76.8 ± 12.1 % respectively while BI activation rates were 71.2 ± 22.1 % and 83.5 ± 12.3 % respectively with no statistically significant difference between sessions and groups. The UNI ERD of contralateral/affected hemisphere was significantly stronger than ipsilateral/healthy hemisphere in all groups ($p=0.002$ for all) while BI ERD was not different between hemispheres. When UNI and BI ERD during AM were compared on the contralateral (lesioned) side corresponding to UNI session, UNI ERD was found to be greater in CO ($p=0.0137$) group. There were no statistically significant differences in ERD between groups.

Discussion

The ERD results show that UNI movements result in predominantly contralateral activity while BI movements result in bilateral activity. This has been shown for healthy volunteers [7], but for people with stroke, the unaffected hemisphere has been shown to inhibit the affected hemisphere [8]. This inhibition can cause attenuation of ERD in affected hemisphere and is inversely related to motor impairment [9]. Recovery is also accompanied with the BI movement related brain activation becoming symmetrical [10]. Most of the participants in ST group did not have severely affected movement, likely why inhibition was not seen, and ST group performed the same as CO group. However, BI BCI-FES could still be used by people with severely affected movements by weighing affected hemisphere activation more. The UNI ERD was found to be greater than BI ERD in CO group. Studies have found stronger ERD for BI movements but differ in location and depend on frequency band and difficulty of task [7], [11]. We used subject-specific frequency band and simpler in-phase BI movement. There were no differences in ERD between groups either. Therefore, ST group without any significant cognitive issues could control BI BCI-FES system without attenuating activation of the affected hemisphere. The results of this study indicate that BI BCI-FES could be used as an adjuvant to UNI BCI-FES for people with stroke induced mild to moderate motor impairment.

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TRANS-SPINAL ELECTRICAL STIMULATION FOR IMPROVING TRUNK AND SITTING FUNCTION IN TETRAPLEGICS WITH CERVICAL CORD INJURY

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ABSTRACT: The aim of this study was to examine the efficacy of trans-spinal electrical stimulation (tsES) for improving trunk control and sitting stability with task specific rehabilitation (tsR) in peoples with chronic tetraplegia. 3 individuals with complete (AIS-A) cervical (C5-C8) spinal cord injury were enrolled in this 6-month clinical study. The combined intervention of tsES and tsR were given for 12 weeks followed by only tsR for another 12 weeks. The stimulating sites were T11 and L1, and the stimulation frequency was from 20-30 Hz with 0.1-1 ms pulse width modulated at 9.4 kHz biphasic stimulation. The functional outcome scales used were Modified Functional Reach Test, Trunk Control Test and Function In Sitting Test. The kinematics assessment was conducted through electromyography and VICON motion capture system. After the combined intervention, participants were able to perform supine to prone movements, independent sitting for longer time in upright erect posture with help of upper extremity and could maintain static and dynamic, trunk and sitting balance with no external assistance for 2-3 minutes with eyes closed. It is not conclusive yet until we do the tsR and would update the results in next 12 weeks.

Keywords: trans-spinal electrical stimulation, trunk control, sitting balance, tetraplegia, spinal cord injury

Introduction

Trunk and sitting control have been valued equally with functional movements in people with higher levels of spinal cord injury (SCI) (Abou et al., 2018, Triolo et al., 2013). Tetraplegics are at higher risk of falls and related injuries among all the SCI patients (Wirz & van Hedel, 2018) Furthermore, poor seating posture results in deformity to the spine and may cause associated complications (Bolin et al., 2000, Minkel, 2000). Hence, restoration of trunk functions to maintain stability in

sitting position is important for effective rehabilitation in cervical SCI patients.

Methods

After a baseline test, combined intervention of tsES and tsR were given for 12 weeks followed by only tsR for another 12 weeks. The stimulating sites were T11 and L1, and the stimulation frequency was from 20-30 Hz with 0.1-1 ms pulse width modulated at 9.4 kHz biphasic stimulation. The subjects were connected to the tsES based on following protocols and tsR exercises were delivered for 45-60 minutes which comprises of three sessions of 15-20 mins followed by breaks between each session. The blood pressure was regularly monitored during the session. And the stimulation was kept off during the rest period. tsR activities combined of spinal mobility exercises such as flexion, extension, rotation along with static and dynamic sitting balance exercises, rolling in supine, etc. The subjects were trained in different environments and positions, as sitting in wheel chair, in bed and floor mat with assistance and supervision by the certified physiotherapist. The functional assessment was conducted using: (1) Modified Functional Reach Test (mFRT) - to observe the reaching distance and to evaluate the risk of fall from wheelchair, (2) Trunk Control Test (TCT) - to assess the static and dynamic equilibrium, and (3) Function In Sitting Test (FIST) - to measure the functional sitting balance. Similarly, kinematics assessment was performed through VICON motion capture system to measure the range of motion parameters of the spine and electromyography (EMG) of the key muscles- rectus abdominis, external oblique, erector spinae and latissimus dorsi responsible for trunk and sitting control.

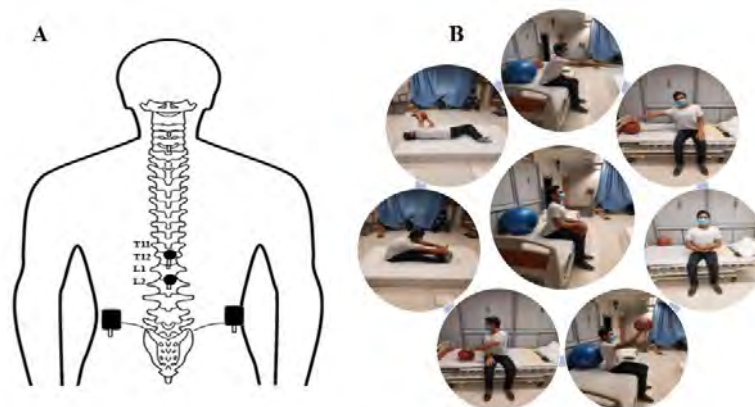


Figure 1: (A) Placement of the electrodes at T11 and L1 with ground electrode over the iliac crest. (B) Task specific rehabilitation exercises in sitting and lying position.

Results

After the combined intervention, participants were able to perform supine to prone movements, independent sitting for longer time in upright erect posture with help of upper extremity and could maintain static and dynamic, trunk and sitting balance with no external assistance for 2-3 minutes with eyes closed. Also, each participant was able to perform anterior, posterior and

lateral scooting with support of upper limbs. Simultaneously, the kinematics assessment showed improvement in the range of motion parameters (flexion and rotation) of the spine with improved stability along with activation of the key muscles (erector spinae, latissimus dorsi) of the trunk supporting to maintain static and dynamic balance.

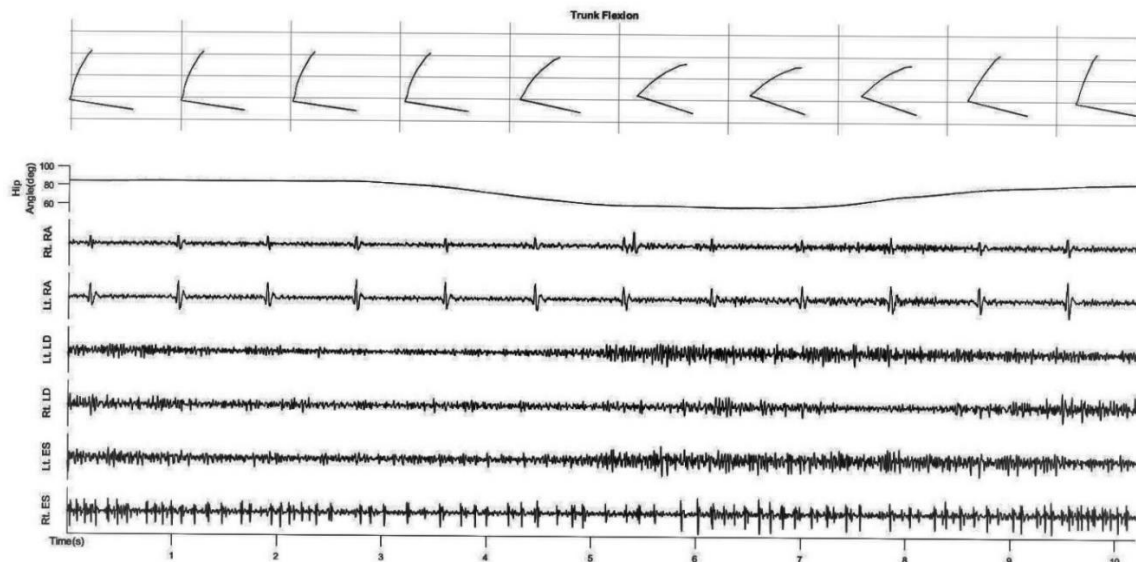


Figure 2: Trunk flexion in sitting with feet placed on the floor with knees and hip at 90 degrees. EMG showing the activation of erector spinae and latissimus dorsi. (RA=Rectus abdominis, LD=Latissimus dorsi, ES=Erector spinae,)

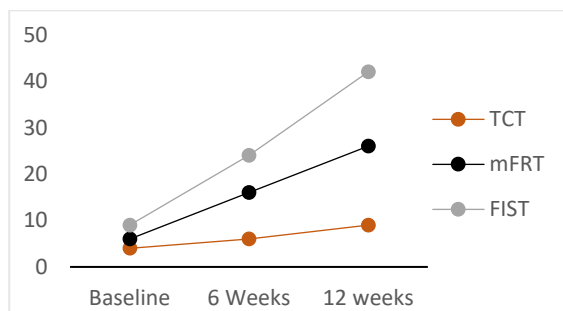


Figure 3: Progression of the functional abilities on trunk control, reaching and sitting balance.

Discussion

There are found to be limited number of researches using spinal electrical stimulation in trunk study. It is reported that spinal stimulation at greater intensities (>80 mA) activates the trunk musculature and forward pelvis tilt and this helps to maintains posture (Al'joboori et al., 2020). Also, the stimulation of L1-L2 site at 15Hz frequency enables extension of trunk muscles leading towards postural stability (Rath et al., 2018).

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The SOCC™: Smart Ongoing Circulatory Compressions

A Wearable Device for the Prevention of Deep Vein Thrombosis

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Abstract: Deep Vein Thrombosis, blood clots that commonly form in the legs, can result in a life-threatening condition known as pulmonary embolism. The SOCC™ is a wearable system that delivers a patented functional electrical stimulation (FES) pattern that activates the muscles of the legs to facilitate venous blood flow. The increased venous blood flow helps prevent blood clots from forming, reducing the incidence of pulmonary embolism.

Keywords: DVT, FES, Wearable, Wireless

Introduction

Deep vein thrombosis (DVT) occurs when a blood clot forms in the deep veins of the body, typically the legs [1]. The most serious complication of DVT occurs when the blood clot is dislodged and travels through the bloodstream to the lungs where it can cause a pulmonary embolism (PE), which may result in death [2]. Venous stasis, is a condition where blood flow in the veins is reduced, and leads to an accumulation of platelets and thrombin in veins that can cause DVTs [3]. People experiencing limited mobility as a result of a medical condition (e.g., bed rest after a surgical procedure) or space restrictions (e.g., airline or vehicle travellers) are at higher risk of developing a DVT due to stasis.

Intermittent pneumatic compression (IPC) devices are commonly used in post-surgical applications to squeeze the legs mechanically to assist venous blood flow [4]. These devices require the wearer to be either laying down (supine) or reclined with legs extended. IPC devices are impractical for use outside healthcare facilities or residences.

Electrical muscle and nerve stimulation has been used to facilitate venous blood flow. The Geko™ OnPulse™ and the VEINOPLUS® V.I. are commercially available stimulators that have demonstrated increases in venous blood flow[5,6]. The Geko™ OnPulse™ device stimulates the common peroneal nerve once per second causing a twitch in the tibialis anterior (shin) muscle.

The VEINOPLUS® V.I. delivers stimulus pulses from 2 to 120 pulses per minute causing twitches in the calf muscle. Both devices stimulate continuously and prolonged use can result in muscle fatigue.

Tetanic (fused) contraction of the calf muscles when walking naturally squeezes the deep veins of the legs, pumping blood back up to the heart. This calf muscle pump [7] is also referred to as a “second heart” [8].

A study conducted in our lab comparing tetanic muscle contractions to muscle twitches showed that tetanic contractions were more effective at increasing peak blood velocity in popliteal and femoral veins [9].

DVT blood clots can form in just a few minutes, so regular contractions of the leg muscles is required. We found that a pattern of 2 seconds of stimulation every 2 minutes was effective and could be sustained for hours without causing muscle fatigue.

Based on our research, we have developed a functional electrical stimulation (FES)-based wearable system for increasing venous circulation in the legs. The system, called Smart Ongoing Circulatory Compressions (SOCC™) has a patented muscle stimulation pattern that results in intermittent alternating contractions of the calf and shin muscles. The calf contractions compress the deep veins in the legs, facilitating increased venous blood flow. Subsequent contractions of the shin muscles (tibialis anterior) stretch the calf muscles, returning the foot to a neutral position while also producing an additional increase in venous flow.

Methods

The SOCC™ consists of a garment worn on the legs with integrated mesh electrode placement windows, a small two-channel muscle stimulator per leg, and a charging dock.



Figure 1: a)SOCC™ Garment b) Stimulators in charge dock

Garment: The SOCC™ form-fitting garment (Fig. 1a) was designed and manufactured in-house, and is worn on the legs. Four mesh windows in the garment enable locating hydrogel surface electrodes over the stimulation sites of the calf and shin muscles. The hydrogel layer of the electrodes penetrates through the mesh to come in contact with the skin. Straps on the garment hold the stimulator in place, and fabric channels help to contain electrode wires.

Stimulation: Each stimulator has two stimulation channels that provide interleaved constant current pulses. Pulse amplitudes up to 60mA can be adjusted independently for each stimulation channel. The remaining pulse parameters (frequency, pulsewidth, and waveform) are common to both channels. The stimulation frequency can be set from 20Hz to 100Hz in 5Hz increments. The primary pulsewidths can be set to 250μs, 300μs or 350μs. One of three possible biphasic waveforms can be selected: symmetrical, with the secondary pulse the same amplitude and pulsewidth as the primary; assymetric, with the secondary pulse half the primary amplitude and twice the pulsewidth of the primary; or assymetric, with the secondary pulse one quarter the amplitude and four times the pulsewidth of the primary pulse.

Stimulation Pattern: The patented stimulation pattern is programmed to deliver two seconds of stimulation to the leg muscles every 2 to 5 minutes, repeating for the duration of treatment. The two seconds of stimulation include one second of calf muscle stimulation (gastrocnemius muscles) followed by one second of tibialis anterior muscle stimulation (ankle flexor).

Microprocessor: The stimulator uses a Nordic Semiconductor nRF52840 system on a chip (SoC) which combines an ARM®Cortex®-M4 32-bit processor with a 2.4GHz software programmable radio. This chip has 256kB of RAM and 1 Megabyte of flash memory which is used for program memory and to store usage data.

OutputStage: The output stage of the stimulator uses an H-bridge configuration with current feedback. Stimulation voltages and currents are monitored by the microprocessor to ensure correct operation.

Wireless Connectivity: The SOCC™ stimulator uses the Bluetooth® Low Energy (BLE) protocol to communicate with external devices such as mobile phones and tablets.

Mobile App: An Android® mobile app was developed using Android Studio. The mobile app allows the user to set stimulation parameters and to control the stimulators.

Battery: The stimulator is powered by an internal, rechargeable, 350mAh lithium polymer battery. The battery can power the stimulator for approximately 30 hours of use.

Charge Dock: The charging dock was designed to charge two SOCC™ stimulators simultaneously (Fig. 1b). The dock connects to a USB charging adaptor or port. The charging current for both devices is limited, and both can be charged through a standard 500mA USB port.

Enclosures: The enclosures for the stimulator and the charge dock were designed over a number of iterations using AutoDesk Fusion 360 CAD software. A Raise3D Pro2 printer was used to make prototype models of the enclosures to test fit and functionality. To achieve flame retardant properties required for Canadian Standards Association (CSA) approval, the final enclosures were made using vacuum casting with Hei-Cast 8263 flame retardant polyurethane.

Results

The effectiveness of the SOCC™ stimulation pattern in increasing venous flow was previously demonstrated in neurologically-intact and post-stroke study participants and validated using ultrasound [9].

Only small tetanic (fused) muscle contractions (<25% of maximal voluntary contraction) were needed to produce significant increases in venous flow in both the popliteal and femoral veins.

Figure 2 shows peak blood velocity in the popliteal and femoral veins resulting from different stimulation patterns. Tetanic muscle contractions were found to be more effective than muscle twitches for increasing venous blood velocity in the popliteal and femoral veins.

The stability of peak venous velocity and flow over time is shown in Figure 3. Tetanic contractions were delivered for 2 seconds every 3 minutes for a duration of 2 hours. The results were normalized to the average responses of the first 3 pulse trains, and then averaged between the 4 study participants. The consistent result over time suggests the intermittent stimulation pattern can be used effectively for extended periods of time.

The stimulated muscle contractions caused little discomfort and no muscle fatigue, suggesting that the SOCC™ can be used for up to 24 hours/day.

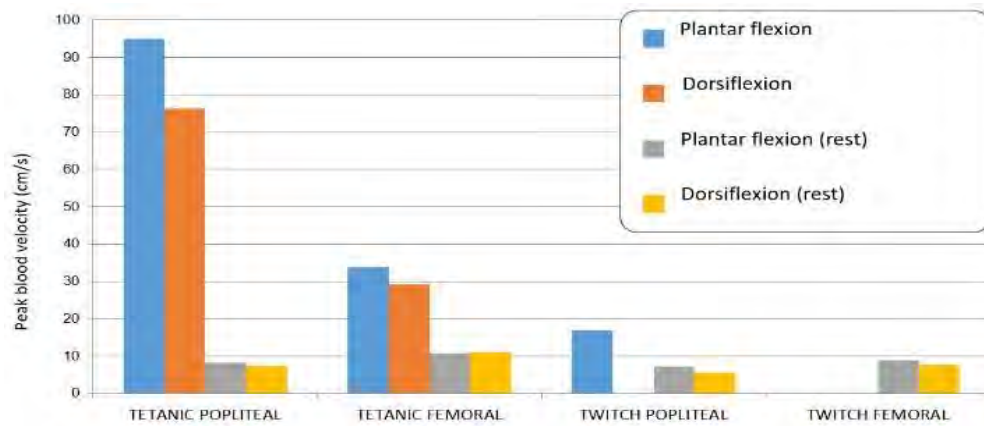


Figure 2. The effect of tetanic muscle contractions vs. muscle twitches on blood velocity in popliteal and femoral veins. Rest plantar flexion and dorsiflexion peak venous velocities refer to baseline venous velocity in the absence of contractions. Plantar flexion and dorsiflexion peak venous velocities refer to the increase in peak venous velocities beyond the rest levels.

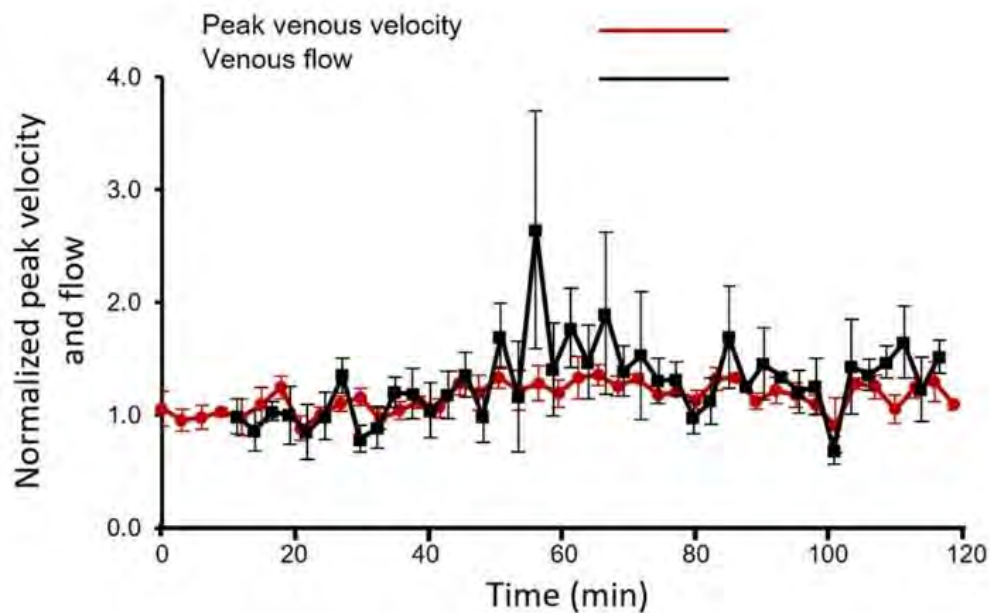


Figure 3. Normalized peak venous blood velocity and flow over time with 2 seconds of stimulation every 3 minutes.

Discussion

The SOCC™ stimulation system is effective for increasing venous blood flow in users who are seated or reclined. The pattern of stimulation used will allow the device to provide enhanced venous blood flow for extended periods of time without fatigue.

In order to make the system acceptable to users, it must be easy to set up and use. Particular attention was paid to reducing the size of the stimulator. The wireless interface allows the stimulator to be controlled by a mobile device app. The mobile app eliminated the need for a display on the stimulator, which is particularly useful since the stimulator is worn on a person's legs. A simple button

interface and LED indicators allow the user to access the basic functions of the stimulator without using the mobile app.

The garment design is still under development. We know that ease of donning and doffing the garment will be a critical factor in the acceptance of the SOCC™ in both personal and clinical environments. We expect that our use of fabric mesh windows in the garment will make donning the garment and applying the hydrogel electrodes easier. Further in-house and end-user testing will be performed in the near future to test our assumptions. Infection control is an important concern for wearable FES devices. For this reason SOCC™ garments will not be shared between users. Normal contraindications for

surface electrical stimulation will apply (e.g. no open sores or other skin integrity issues). The garment is designed to be hand washed for reuse by the user. Limitations on reusing the garment and hydrogel electrodes have yet to be determined.

If successful, this system may fill a much needed gap in the prevention of DVT.

Acknowledgement

This work was supported in part by the Canada Foundation for Innovation, the Canadian Institutes of Health Research, and Smart Technology (ST) Innovations, the business arm of the SMART Network, funded by the Government of Alberta Department of Jobs, Economy and Innovation.

The SOCC™ system will soon be utilized in study participants at home and in acute hospital settings to assess its safety, feasibility and acceptability. Future clinical trials will assess the effectiveness of the system in preventing DVT in comparison with IPC devices.

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A COMBINED APPROACH TO CNS EXCITATION FOR HAND REHABILITATION: A CASE STUDY USING SPINAL STIMULATION AND BCI

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Abstract: *Transcutaneous electrical spinal cord stimulation and brain-computer interface motor priming have both been used as a means of enhancing motor recovery in neurologically impaired populations. This study aimed to explore the potential benefits of combining both approaches in a single therapy, in effect promoting plasticity at two levels of the central nervous system: the brain and spinal cord. This single-patient study followed a C4 incomplete spinal-cord injured individual over a three-month period as he received intensive upper-limb training whilst receiving cervical spinal cord stimulation, and, for 4 weeks, BCI-motor priming preceding training. This study found improvements in strength and prehension which exceeded thresholds of minimal detectable differences. Although functional improvements were similar both with and without BCI motor priming, sub-scores including muscle strength were more marked when priming preceded training, possibly suggesting an added benefit over stimulation and training alone.*

Keywords: *Transcutaneous electrical spinal stimulation, rehabilitation, motor recovery, brain-computer interface, neurofeedback*

Introduction

Transcutaneous electrical spinal cord stimulation (tSCS) has demonstrated benefits in enhancing hand and arm recovery in spinal cord injury (SCI) patients when combined with intensive massed practice (MP) [1]. By using surface electrodes to inject high frequency currents at the spinal level of injury, posterior roots are excited to sub-threshold levels, making volitional motor control easier through residual descending pathways.

Similarly, motor priming, which often involves repetitive movements aimed at enhancing a subsequent therapy, has been associated with changes in neuroplasticity that have been linked to changes in functional recovery [2]. A brain-computer interface can be used to prime the patient for therapy regardless of their motor impairment level by translating their brainwaves into a motivating a priming paradigm [3].

In this single-patient study we explored the feasibility of targeting the brain and spinal cord with different neuromodulation strategies in an effort to boost the therapeutic benefits of tSCS hand training alone.

Methods

We used a two-phase crossover design for our study whereby the patient underwent fifteen 60-minute sessions of tSCS and massed practice (tSCS+MP) over a five-week period, followed by 15 sessions of tSCS+MP immediately after 30 minutes of BCI motor priming. There was a two-week washout period between phases where no massed practice, stimulation, or priming was delivered.

Patient characteristics: A 40-year-old male participated in this study. His injury, which occurred 12 years before his recruitment into this study, was graded before the study as American Spinal Injury Impairment Scale (ASI) category C.

This study was approved by the Human Subjects Ethics Sub-committee of the Hong Kong Polytechnic University (HSEARS20190121002; 9 Feb 2019) and the patient provided written informed consent.

Massed practice (MP): Hand and arm training consisted of repetitive uni- and bimanual MP training in conjunction with tSCS [4]. A typical session focused on a number of grasp types: palmar grasping, pinching, finger isolation, etc. Tasks included flipping playing cards, moving ping pong balls between containers, scooping rice, stacking blocks, among others. Tasks were adjusted relative to functional improvements to maintain a degree of difficulty. For example, ping pong balls were replaced with marbles and then by small beads as the study progressed. MP was performed continuously over the 60-minute session with two brief pauses when the patient was given a break from tSCS.

Transcutaneous electrical spinal cord stimulation (tSCS): Stimulation was delivered in trains of ten 100 μ s long biphasic rectangular pulses at a frequency of 30 Hz with a DS8R Biphasic Constant Current Stimulator (Digitimer, UK). Two round cathode electrodes (3.2 cm diameter; Axelgaard Manufacturing Co, Fallbrook, CA, USA) were positioned above and below the level of injury between the C4-C5 and C5-C6 intervertebral spaces. Hypoallergenic tape fastened the cathodes to the skin to ensure snug contact throughout the session. Inter-connected anode electrodes (8.9 \times 5.0 cm; Axelgaard Manufacturing Co, Fallbrook, CA, USA) were placed symmetrically on the shoulders, above the acromion. The current intensity was determined at the beginning of each session by slowly increasing the current from zero to the highest intensity tolerable to the patient (mean \pm standard deviation; C4-C5:

49.0 ± 4.6 mA, C5-C6: 40.8 ± 5.1 mA). Stimulation was applied for a total of 60 minutes during each session. For safety reasons there was a two minute break every 20 minutes where the stimulator was switched off. The patient's heart rate and blood pressure were monitored during breaks.

BCI motor priming: The patient was given vertical control over an on-screen photorealistic basketball as it moved across the screen from left to right at a constant rate (Fig. 1). A 'trial' began with the ball on the middle-left of the screen and a rectangular 'target' at either the top-right or bottom-right of the screen. The patient had vertical control as the ball moved from left to right. Mirror symmetric finger flexion would move the ball up and the resting state would move it down. The patient was asked to attempt finger flexion as if they were clutching a real basketball, including imagining the sensation of doing so. There were 10 runs of 30 trials, each trial lasting four seconds, with a randomised 1.5-2.5 s inter-trial interval. There was a 10-60 s break between runs to avoid fatigue.

Demodulation of sensorimotor rhythms was used to control the priming paradigm. EEG was recorded at 256 Hz using a g.USBamp (gtec, Austria) and ten active electrodes positioned at FC3, FC4, C1, C2, C3, C4, C5, C6, CP3, and CP4, according to the international 10-20 system. The EEG was processed using the BCI2000 platform [5]. Incoming EEG was spatially filtered with a large Laplacian and transformed into the frequency domain. A brief 5-minute calibration session at the beginning of each week found the most discriminative frequency between bimanual finger flexion and the resting state. The power at this frequency bin was used to train a linear classifier, the normalised output of which controlled the on-screen ball.

Functional outcomes: The Graded Refined Assessment for Strength, Sensibility, and Prehension (GRASSP) was used as the primary outcome measure [6]. The test was performed every two weeks throughout the study.



Figure 1: During BCI motor priming. A photo-realistic basketball moved across the screen, from left to right, at a constant rate. The participant was instructed to attempt finger flexion as if they were clutching the ball with both hands. Doing so perturbed the ball's trajectory in the upwards direction. Conversely, resting moved the ball downwards. The goal was to hit the rectangular target.

Results

GRASSP scores showed a consistent improvement in upper extremity function over the course of the study, after remaining constant during two baseline measurements (Fig. 2). From a total bilateral score of 96 out of 232 during baseline, four weeks of tSCS+MP increased the score by 21 points, followed by a further 18 points after 4 weeks of BCI priming and tSCS+MP. Taking both phases into account the patient improved a total of 35 points, ending Week 10 with 131 out of 232, a 36% increase from baseline. The total score decreased slightly after the two-week washout phase but remained 18 points above baseline.

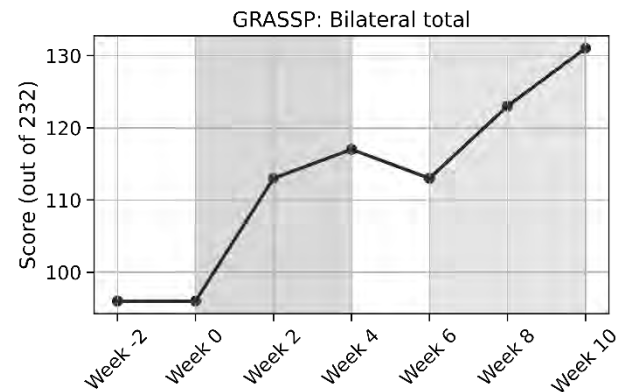


Figure 2: Composite bilateral GRASSP total scores across 12 weeks. The left and right grey columns refer to Phase I (tSCS+MP) and Phase II (BCI-priming and tSCS+MP) respectively.

The most marked improvements were in upper-extremity muscle strength (Fig. 3A). Bilateral manual muscle tests from ten upper-limb muscles showed a six-point increase in strength compared to the baseline average during Phase I (51/100 to 57/100) and an 11-point increase when BCI-priming was added in Phase II (53/100 to 64/100). Only during Phase II does the score improve beyond the minimally detectable difference (MDD) for strength (more than 7 points) [7].

Improvements in strength mostly came from the right side, which was the more impaired side at baseline. During both phases the strength scores on the right side increased by at least the MDD (5 points). The left side, on the other hand, improved significantly only during the priming phase, with a 6-point increase compared to the beginning of phase II.

Sensibility, a measure of fingertip sensation, did not exceed MDD (more than 4 points) during either phase; I: +3.5 and II: +1, for dorsal sensibility, and -0.5 and +3 for palmar sensibility (Fig. 3B). There was, however, a 4.5-point increase in sensibility taking both phases into account, half a point above the MDD threshold.

The final category of the GRASSP, prehension (Fig. 3C), measured coordination and dexterity in functional tasks, such as inserting a key into a lock or removing lids from jam jars. The difference in qualitative score did not reach the MDD threshold (more than 5 points) during either phase: 3.5 (11.5/24 to 15/24) during tSCS+MP and 2 (14/24 to 16/24)

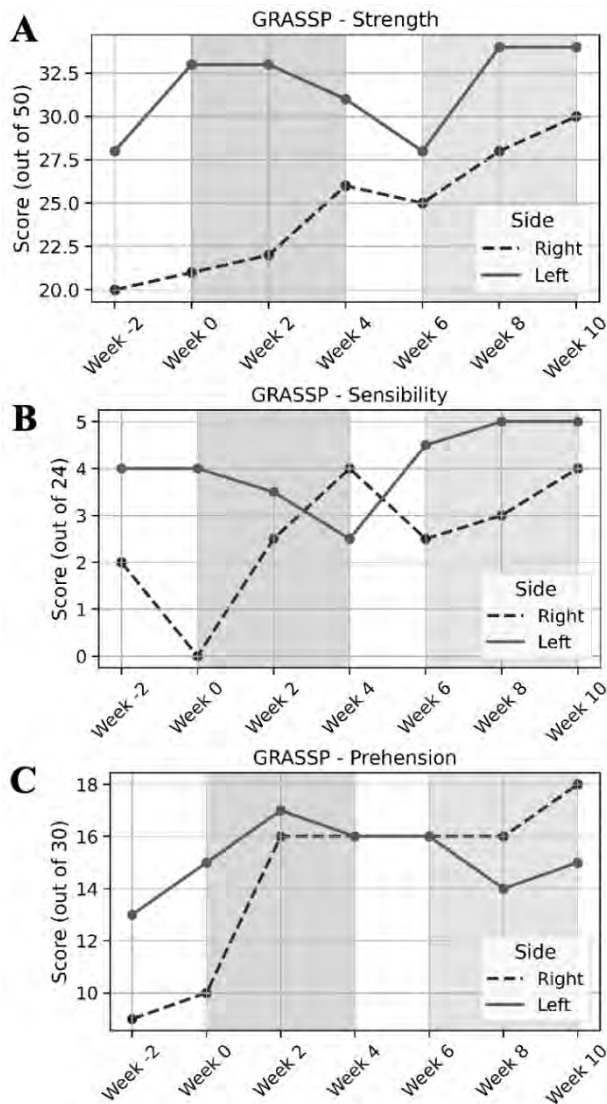


Figure 3: GRASSP component scores: A: Strength, B: Sensibility, C: Prehension. The left and right grey columns refer to Phase I (tSCS+MP) and Phase II (BCI-priming before tSCS+MP) respectively.

during tSCS+MP and priming. On the other hand, the quantitative component of the assessment showed an 8.5-point increase (23.5/60 to 32/60) during Phase I and a 1-point increase during Phase 2 (32/60 to 33/60). Taken together this 9.5-point increase in quantitative prehension exceeds the MDD (more than 6 points).

The spinal stimulation was well tolerated throughout sessions and across the study. The current intensity was set as high as the patient could tolerate, i.e. below his pain threshold. This tolerance was relatively consistent throughout the study. The cathode electrode between the C4-C5 intervertebral space delivered a slightly higher current than the cathode between C6-C7, reflecting the patient's sensitivity in these areas. During a session the patient would become less sensitive to the stimulation and the current could often be raised by a further 10 mA after around 10 minutes of exposure.

BCI motor priming proved effective in decoding the patient's movement intentions and he was able to guide the moving ball to the correct target with high accuracies (>80%) and improved over the course of 15 sessions, with a Pearson's correlation coefficient of 0.65 ($p < 0.01$).

Discussion

This study adds to the ever-growing research supporting the use of transcutaneous electrical spinal cord stimulation for SCI rehabilitation. This work shares similarities with the functional gains made by a single SCI patient study from 2018 by Inanici *et al* [8]. Namely, improvements were mostly found in muscle strength and prehension, with sensation generally unaffected. In 2021, this same group expanded their case study with more patients of varying impairment levels [1]. Improvements from patients with similarly limited thumb and finger movements are in line with the results reported here. This 2021 study also reported instantaneous improvement in motor function during stimulation. The current study, however, did not detect functional gains until after multiple sessions, perhaps reflecting the greater impairment category.

This study intended to explore the effect of BCI priming on tSCS-based therapy. Although not stark, the inclusion of BCI priming may have contributed to enhanced bilateral strength improvement given that without priming the difference in scores did not exceed a minimal detectable difference. A possible explanation is that the focussed mirror-symmetric finger movements made the descending pathways more responsive to the subsequent therapy. The benefit of utilising the patient's EEG included improving compliance, as the game-like nature of the priming paradigm motivated the patient to actively participate.

A potential limitation of this study is that both phases combined stimulation and massed practice. Although the benefits of cervical tSCS on massed practice-based rehabilitation have been demonstrated previously, a future intervention with three arms – tSCS+MP, BCI-priming with tSCS+MP, and MP alone – would help illustrate the effectiveness of combining interventions.

Although enhanced GRASSP scores may be considered indirect evidence of increased cortical and sub-cortical excitability a future study using targeted techniques is required to determine if the CNS was indeed affected by this therapy. Transcranial magnetic stimulation before and after priming, and spinally motor evoked potentials before and after training could be used to quantitatively demonstrate modulation of the nervous system.

Future analyses of this patient study will explore how sensorimotor dynamics were affected by repeated tSCS training sessions and whether this correlated with improved accuracy or functional gains.

Acknowledgement

We are exceptionally grateful for the patience and commitment of the research participant and his carer.

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ANALYSIS OF THE MOVEMENTS GENERATED BY A MULTI-FIELD FES DEVICE FOR UPPER EXTREMITY REHABILITATION

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Abstract: The most common chronic sequela after stroke is the loss of arm function, and functional electrical stimulation (FES) applied to the forearm muscles is one of the options for treating it. Surface multi-field electrodes have emerged, showing great potential on improving selectivity of stimulation, delaying muscle fatigue, and providing easier donning and doffing. The muscular selectivity takes on a special relevance in the rehabilitation of upper extremity, as hand dexterity requires many and very specific muscle actions. This pilot study analyses the movements generated in the wrist and fingers using a commercial multi-field technology-based FES device. 5 persons with hemiplegic subacute stroke participated in the study, where a scanning of all cathodes of the electrode was carried out daily for 5 days and the resulting movements labelled by experienced therapists. Results show that with a commercial multi-field technology-based FES device, 8 different movements of the wrist and the fingers can be achieved with a very high inter-session and inter-patient repeatability.

Keywords: Rehabilitation, functional electrical stimulation, upper extremity, motor function, selectivity.

Introduction

Persons with neurologic diseases often show a limitation or loss of functional capacity of the upper and lower extremities [1]. The most common chronic sequela after stroke is the loss of arm function. In fact, 65% of persons are unable to use their affected hand in daily living activities 6 months after stroke [2]. The lack of functionality can affect the quality of life, producing, in many cases, dependency situations [3]. The most affected movements are the extension of the wrist and hand fingers, being difficult to achieve a complete recovery of them [4].

Functional electrical stimulation (FES) consists of providing short bursts of electrical pulses to elicit action potentials in the motor neurons that innervate muscles, generating muscle contractions and thus, rehabilitating motor function [5]. When used for hand rehabilitation, stimulation is applied to the forearm muscles to produce movements of wrist and finger joints. The scientific evidence widely supports its use, as it has shown to be effective to improve functional [6], biomechanical [7], and neurophysiological parameters [8].

FES devices have been traditionally based on conventional electrodes. However, surface multi-field electrodes have emerged, showing great potential on improving selectivity

of stimulation, delaying muscle fatigue, and providing easier donning and doffing [9]. The muscular selectivity takes on a special relevance in the rehabilitation of upper extremity, while hand dexterity requires many and very specific muscle actions [10].

The aim of this pilot study was to analyse the movements generated in the wrist and fingers by commercial multi-field technology-based FES device, and to determine if there were differences between persons and between sessions in terms of produced movements.

Methods

The Fesia Grasp system (Fesia Technology, Donostia - San Sebastián, Spain) is one of the FES devices used for hand dexterity rehabilitation, delivering a train of biphasic pulses of different widths and amplitudes to different fields of the electrodes in an asynchronous manner [11]. The system (Fig. 1) consists of a stimulating unit, garment with integrated multi-field electrode (comprises 32 cathodes and 8 anodes), and tablet with application. The software application allows to configure the desired stimulation parameters and to monitor the evolution of the persons.



Figure 1: Fesia Grasp device. A: garment; B: stimulator; C: multi-field electrode.

5 persons with subacute stroke (< 6 months since stroke) were included in this study. The laterality was right for 4 of them and left for the other 1. All the participants signed

an informed consent, and the study was approved by the Euskadi Drug Research and Ethics Committee (CEIm-E). The inclusion and exclusion criteria are shown in Tab. 1.

Table 1: Characteristics of included persons.

Inclusion criteria	Exclusion criteria
<ul style="list-style-type: none"> Age: > 18 years. Subacute stroke (< 6 months). Motor dysfunction of the hand caused by stroke. Modified Ashworth Scale < 3. 	<ul style="list-style-type: none"> Peripheral Nervous System Injury or Disease. Modified Ashworth Scale > 2. Severe muscle contractions in the affected forearm. Pacemaker. Ventriculoperitoneal shunt devices. Osteosynthesis material or metal implants. Skin lesions of the affected forearm. Serious behavioural disturbance. Pregnancy.

One scanning was held daily during 5 days with 5 subjects. Each scanning consisted of carrying out a cycle of stimulations throughout the electrode, activating each of the 32 cathodes individually (in pseudo-random order). During the scanning, two experienced occupational therapists analysed the movements that were generated during stimulation of the cathodes, and assigned them to one or more of the following categories:

- Wrist: neutral (no movement), flexion, and extension.
- Fingers 3, 4, and 5 (“fingers”): neutral (no movement), flexion, and extension.
- Index: neutral (no movement), flexion, and extension.
- Thumb: neutral (no movement), flexion, and extension.

Stimulation waveform was biphasic compensated, and parameters were set to frequency 35 Hz and pulse width 300 μ s. The amplitude was set for each day and person at 5 mA above motor threshold if tolerated by the subject, otherwise above motor threshold at person’s tolerance. The motor threshold was defined as the minimum amplitude at which wrist or fingers movement was visually appreciated with one of the fields.

During the configurations, the persons were seated in a chair and rested their arm on top of a table with an elbow angle of 90 degrees. The forearm was kept in neutral position and rested on top of a pillow.

The analysis focused on the movements assigned by the therapists depending on the stimulated cathode. The aim was to analyse the movements generated by the system, and to determine if there were differences between persons and between sessions in terms of produced movements.

Results

A total of 800 stimulations were performed, 160 in each subject (32 stimulations each of the five days).

Figure 2 shows the proportion in which each of the movements was generated in each joint for all the subjects.

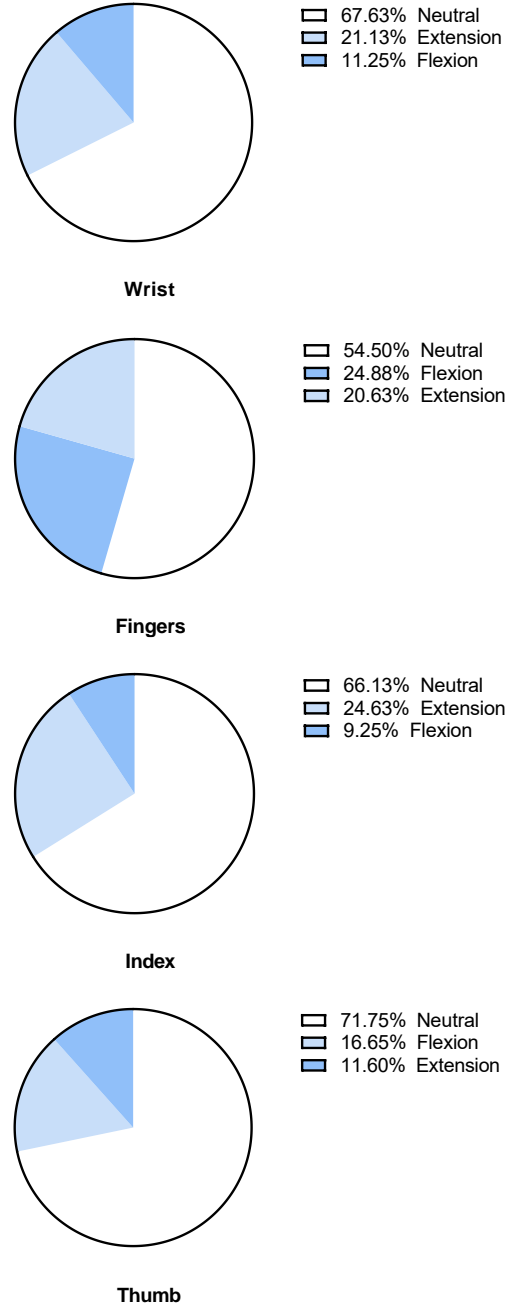


Figure 2: Proportions of all the movements generated in the wrist, fingers, index, and thumb joints in all subjects.

If we focus on wrist, extension was detected 189 times (21.13%) and flexion 90 times (11.25%). No movement (“neutral”) was detected 541 times, which is equivalent to 67% of the stimulations. On the other hand, in the fingers, flexion and extension movements occurred 199 (24.88%) and 165 (20.63%) times, respectively. The number of stimulations in which there was no movement of the fingers

was 436 (54.5%). Regarding the index, the stimulation produced an extension 197 times (24.63%), a flexion 74 times (9.25%), and no movement 529 times (66.13%). Finally, the results of the movements generated in the thumb are the

followings: neutral, 569 times (71.75%); flexion, 139 times (16.65%); and extension, 92 times (11.6%).

In Figure 3, the classification results obtained in different subjects are shown.

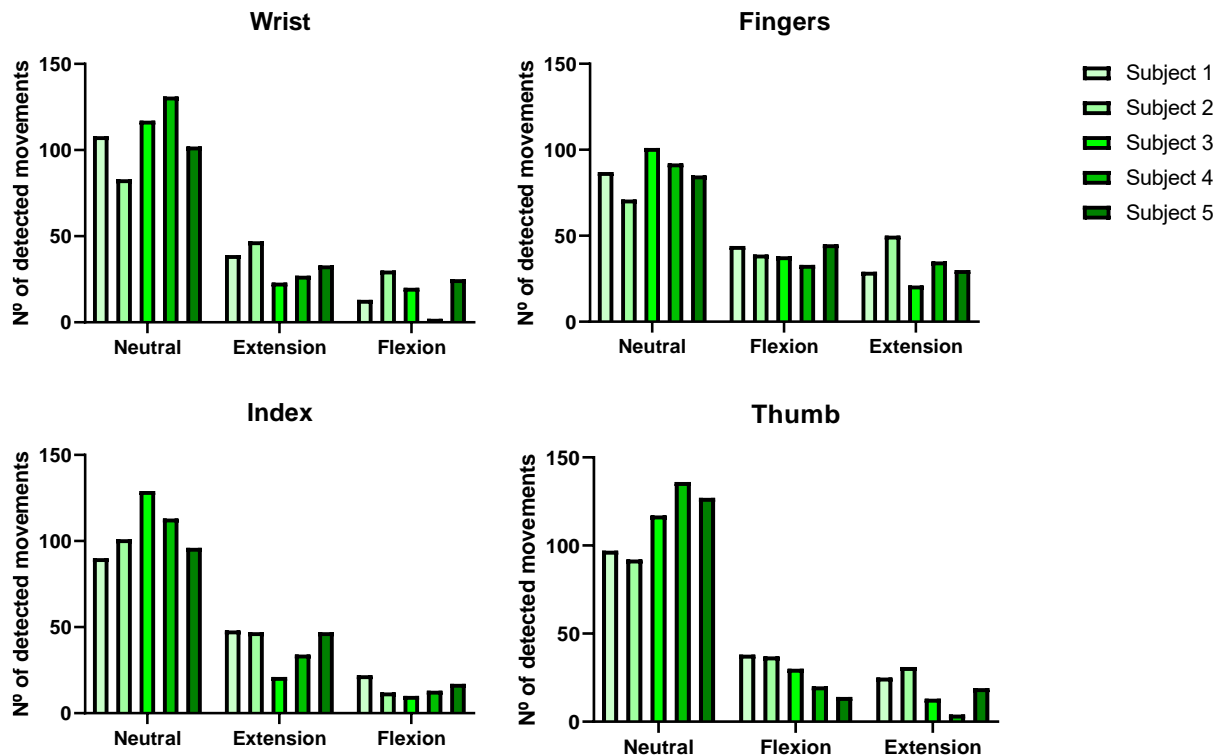


Figure 3. Wrist, fingers, index, and thumb movements generated by all the stimulations for each subject.

Although the difference was slight, in the wrist and the index, the extension (wrist, 14.38-29.38%; index, 13.13-30%) was the predominant movement over the flexion (wrist, 1.25-18.75%; index, 6.25-13.75%). In the case of the fingers, the flexion (20.63-28.13%) was generated more times and more regularly than the extension (18.13-31.25%). Something similar happened in the thumb, a finger in which flexion (8.75-23.75%) occurred more times than extension (2.5-19.38%).

As can be seen in Fig. 3, the generated movements were very similar between patients. The eight movements appeared in all the 25 sessions, except for 3 sessions in which it was not possible to generate wrist flexion in Subject 4, and 1 session in which it was not possible to produce wrist extension in this same subject.

Discussion

As we stated earlier, the aim of this study was to analyse the movements generated by a multi-field FES device, and to determine if there were differences between persons and between sessions in terms of produced movements.

This analysis proved that with a multi-field technology-based FES device at least 8 different movements of the wrist and fingers joints can be achieved with very high inter-session and inter-patient repeatability.

This great variety of movements generated could provide enormous benefits at the clinical level, as it could allow to train functional activities more precisely.

Regarding the variability between movements, the greater presence of extension movements could be due to the fact that the average size of the extensor muscles is bigger, filling a greater surface than the flexor muscles. Beyond a problem, this could be a benefit, since, as previously mentioned, the most affected movements are the extension of the wrist and hand fingers [4].

As mentioned, the inter-patient and inter-session repeatability in the generated movements was very high, obtaining all movements in all patients and in almost all sessions. This could be since the multi-field electrode can generate stimulations in many different parts of the forearm, making it possible to adapt to anatomical differences between persons. It could bring gains in the usability of the device since all movements will be able to be achieved with an only position of the electrode. These improvements in terms of usability have already been described in other applications of multi-field FES electrodes, such as foot drop rehabilitation [9]. The occasions in which no movement could be achieved were residual and occurred always in the same person (Subject 4). This could be due to some anatomic difference of the person and could be solved by slightly varying the position of the electrode.

We conclude that the multi-field electrode of Fesia Grasp allows to generate a wide range of movements of the hand. This fact allows to generate more physiological movement patterns during the rehabilitation process with FES, which could have a beneficial effect on the recovery of the persons with neurological diseases. Furthermore, the high

inter-session and inter-patient repeatability in the generated movements could bring benefits in terms of usability. This pilot study should be carried out in a bigger and more heterogeneous population in order to confirm the present conclusions. In addition, further research is necessary to elucidate the repeatability of the generated movements by multi-field FES devices for hand dexterity rehabilitation.

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NEUROMUSCULAR AND FUNCTIONAL ELECTRICAL STIMULATION FOR MOTOR RECOVERY AFTER COVID-19: SYSTEMATIC REVIEW

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Abstract: COVID-19 produces persistent and prolonged effects, also in the motor function, and its rehabilitation is often complex and challenging. Electrical stimulation (ES) could have an important impact in the rehabilitation of persons with COVID-19. Neuromuscular electrical stimulation (NMES) and functional electrical stimulation (FES) have been proposed as alternatives for motor function rehabilitation in persons with COVID-19. The aim of this study was to systematically review the articles published to date dealing therapeutic effects of NMES and FES in the motor rehabilitation of people with COVID-19. A systematic search of electronic databases was conducted, and articles related with the use of electrical stimulation in persons with COVID-19 for motor recovery were included. A total of fifty-three citations were found, of which eleven were eligible for inclusion. Considering the action mechanism of ES, and its effectiveness in similar cases, it could be an effective technique for the rehabilitation of motor function in persons with COVID-19. However, it is necessary to carry out clinical trials to confirm this hypothesis. In addition, FES, and more specifically FES-cycling, could have additional beneficial effects over NMES.

Keywords: Rehabilitation, COVID-19, electrical stimulation, motor function, review.

Introduction

Coronavirus disease 2019 (COVID-19) is recognized as a multi-organ disease with a broad spectrum of manifestations. There are reports of persistent and prolonged effects after acute COVID-19, also in the motor function [1]. The motor rehabilitation of persons with COVID-19 after treatment in the intensive care unit (ICU) is often complex and challenging [2]. The importance of the rehabilitation of the motor function of the extremities has been widely demonstrated, as it is a very important component for the performance of the activities of the daily living [3]. Electrical stimulation (ES) is a technique in which small electrical pulses are applied to skeletal muscle to cause contractions [4]. It can increase muscle strength [5], prevent muscle atrophy [6], reduce oedema [7], and increase the activity of the nervous system [8]. These effects could have an important impact in persons with COVID-19 [4]. The most relevant types of ES applied to neuromuscular structures are neuromuscular electrical stimulation (NMES) and functional electrical stimulation (FES), and both have been proposed as alternatives for motor function rehabilitation in persons with COVID-19 [9]. NMES involves the application of a series stimuli to superficial skeletal muscles, with the objective to trigger visible muscle contractions. On the other hand, FES, refers to the process

of pairing the stimulation simultaneously or intermittently with a functional task [10].

There is a growing body of publications about motor rehabilitation of individuals with COVID-19 using ES. Thus, the aim was to review the articles published to date dealing therapeutic effects of NMES and FES in the motor rehabilitation of people with COVID-19.

Methods

A systematic search of electronic databases was conducted in June 2020 by accessing three online databases (Cochrane Library, PubMed, and PEDro). The search keywords were “electrical stimulation”, and “COVID-19”.

Articles related with the use of electrical stimulation in persons with COVID-19 for motor recovery were included.

Due to the limited number of known controlled trials in this field of study, the review was purposefully inclusive, including empirical research, and studies of both observational and experimental design evaluating ES as an intervention. Opinion pieces, narrative reviews, study protocols, hypotheses and case reports were also included. No restrictions were place on publication date.

After the systematic search of databases, duplicates and obviously irrelevant articles were removed. Articles were initially screened by title and then by abstract. Publications that met the inclusion criteria were read in full to confirm eligibility (Fig. 1).

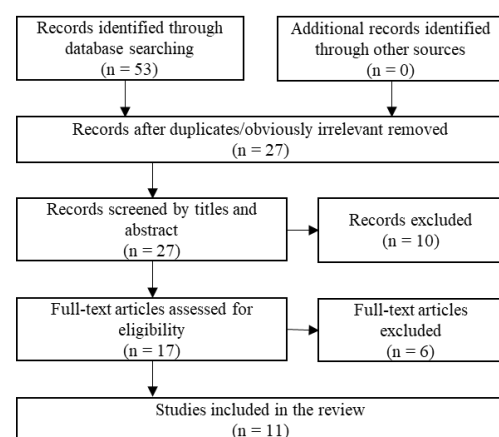


Figure 1: Flow diagram.

Results

A total of fifty-three citations were found, of which eleven were eligible for inclusion. Included publications, article types, ES modalities, and a summary of each of the publications are shown in Tab 1.

Table 1: Characteristics of included articles.

Author (year) and reference	Article type	ES modality	Summary
Allawadhi et al. (2020) [11]	Hypothesis	FES	Authors hypothesize that ES can be a potential adjuvant to the currently used therapies and drugs, and they propose that ES can improve respiratory functions, inhibit SARS-CoV-2 growth, reduce pain, boost immunity, and improve the penetration of antiviral drugs.
Burgess et al. (2021) [4]	Review	NMES	This review examines the evidence, current guidelines, and proposed benefits of using NMES with persons admitted to the ICU. NMES may play a role in the weaning of persons from ventilators and can be continued in the post-acute and longer-term phases.
Carraro et al. (2021) [9]	Point of view	FES and NMES	The authors suggest that, in addition to strength exercises, leg muscles could be trained also by an adjunctive NMES in frail old persons with fatigue syndrome after-COVID-19.
Deley et al. (2021) [12]	Letter	FES-cycling	Response to Nakamura [17]. The authors explain that it is essential that early rehabilitation following COVID-19 also targets cardiovascular, cognitive, functional, and mobility reconditioning. Such benefits require exercise intensities that might not be reachable with belt-type EMS. The authors think that FES-cycling could be a solution since it involves a great muscle mass during a functional movement.
Frydenlung et al. (2021) [13]	Case report	NMES	A hospitalised person with COVID-19 who received unilateral NMES treatment maintained muscle mass as well as maximum voluntary quadriceps contraction and balance.
Mateo et al. (2021) [14]	Proof-of-concept controlled study	FES-cycling	This study investigated whether the erectus position restoration and walking resumption in persons with a critical form of COVID-19 could be accelerated by rehabilitation combined with FES-cycling or with cycling alone in an early stage immediately after ICU discharge. Persons who benefitted from FES-cycling had a significantly greater daily-life physical activity recovery profile.
Minetto et al. (2021) [15]	Study protocol of a randomized controlled trial	NMES	Description of the study design, protocol, content of interventions, outcomes and to discuss the clinical rehabilitation impact of the expected experimental results. This prospective, randomized, controlled, parallel-group, single-blind trial will include 80 persons who had undergone mechanical or non-invasive ventilation following pneumonia-induced respiratory failure. Persons are randomized to a control group (routine physical therapy) or a NMES group (routine physical therapy + NMES).
Najafi et al. (2020) [16]	Study protocol of a randomized controlled trial	FES and NMES	The purpose of this study is to test feasibility and proof-of-concept effectiveness of lower extremity ES therapy to address chronic morbid consequences of COVID-19. All persons will receive daily ES (FES or NMES) in lower extremity up to 1 hour. The primary outcomes include muscle function, muscle strength, lower extremity tissue oxygen saturation, neuropathy, and muscle atrophy.
Nakamura et al. (2020) [17]	Letter	NMES	The authors propose that automated NMES is expected to be an ideal mobilization for severe COVID-19 persons. Belt-type NMES is expected to be effective because it can induce whole lower extremity exercise through whole muscle contraction between wrapped belts.
Ozyemisci-Taskiran et al. (2021) [18]	Observational study	NMES	The aim is to evaluate the effects of early rehabilitation program in ICU in 35 persons with acute respiratory distress syndrome secondary to COVID-19. Early rehabilitation program consisted of range of motion exercises and NMES in addition to standard intensive care and was compared to standard intensive care. There was no difference in strength following discharge between groups.
Sagarra-Romero et al. (2020) [19]	Review	NMES	It describes the scientific evidence for an early strength intervention, NMES or the application of heat therapy during hospitalization to prevent COVID-19 functional sequels. The use of ES is a strategy of intervention with positive effects in seriously ill hospitalized persons who are unable to perform resistance exercises.

Articles for review included one hypothesis [11], two reviews [4,19], one point of view [9], two letters [12,17], one case report [13], one proof-of-concept controlled study [14], two study protocols of randomized controlled trials [15,16], and one observational study [18].

Five articles included FES [9,11,12,14,16] (two of them, FES-cycling [12,14]), and eight articles included NMES [4,9,13,15-19]. Two studies included both FES and NMES [9,16].

Discussion

This review of eleven articles aimed to summarize the articles published to date dealing therapeutic effects of NMES and FES in the motor rehabilitation of people with COVID-19. To our knowledge, this is the first review to specifically evaluate the scientific publications about this topic.

The results of the review do not allow us to elucidate whether ES is an effective and efficient technique for the rehabilitation of motor function in people with COVID-19 or with sequelae after the disease. Considering its action mechanism, the benefits could have a positive effect on persons with COVID-19, as it already has in other persons admitted to the ICU [4,19]. Although early evidence does suggest that this could be the case in COVID-19 as well, randomized and controlled clinical trials showing these positive results have not yet been published.

About the type of current, although a greater number of studies mention NMES [4,9,13,15-19], those that mention FES [9,11,12,14,16] also have strong arguments. FES involves ES during a functional task, which could increase the effect of therapy, adding additional benefits to those provided by NMES [12,16]. In many situations, persons in very acute phases of the disease are going to be treated, and FES-cycling seems to be an ideal technique for these cases [12,14]. It is a modality that, although performed in a sedation or supine position, requires a lower collaboration and basal state than other functional movements (for example, walking), allowing therapists to start applying FES from earlier phases of the disease, which could accelerate the recovery process.

Protocols of randomized and controlled clinical trials that are being carried out have been published [15,16], and their results could respond to the hypotheses raised so far by the clinical and scientific communities.

As a conclusion, considering the action mechanism of ES, and its effectiveness in similar cases, it could be an effective technique for the rehabilitation of motor function in persons with COVID-19. However, it is necessary to carry out clinical trials to confirm this hypothesis. In addition, FES, and more specifically FES-cycling, could have additional beneficial effects over NMES, as it would allow to start the training of functional actions from earlier stages of the disease.

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Evaluation of Cumulative Charge Activation Technology in Decreasing Delayed-onset Muscle Soreness after Eccentric Exercise

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Abstract: *This study aimed to examine the treatment efficacy of noninvasive neuromuscular stimulation, specifically cumulative charge activation technology (CCAT) by (1) quantifying healing responses of musculoskeletal tissues experiencing DOMS post-eccentric exercise; and (2) quantifying symptoms of delayed-onset muscle soreness (DOMS) in treatment versus control groups.*

Untrained, healthy subjects (n=24) were randomly assigned to treatment and control groups and performed an eccentric exercise protocol designed to elicit a DOMS response in elbow flexor muscles. The Control group recovered without post-exercise treatment; while the Treatment group received 5 treatments of CCAT (using the Sigma Q® Bioneuro system) at 2 hours, 1, 2, 4 and 8 days post-exercise. Outcome measures collected to measure tissue damage and healing responses included: serum Creatine Kinase (CK) levels, relaxed elbow angle (REA), and maximum voluntary isometric contractions (MVICs). A survey was used to obtain subjective symptoms before and after exercise in both groups. ANOVA with repeated measures and linear regression techniques were used to examine objective and subjective outcomes.

The recovery slope of the REA in linear regression model was significantly different from zero ($T=2.92$, $p<0.01$) and almost twice as great as the Control group's ($T=1.39$, $p=0.169$). Serum CK levels and MVICs were significantly associated with Day ($p<0.05$), but not Treatment ($p>0.05$) effects. Self-reported soreness/stiffness of the exercised arm ($p<0.001$) and arm pain ($p<0.05$) demonstrated a Treatment x Day interaction, and simple main effects demonstrated decreased symptoms for the Treatment group on certain days.

CONCLUSION: *Treatment with Sigma Q® Bioneuro-based CCAT was associated with reduced symptoms of stiffness/soreness and pain, and increased rate of recovery of REA.*

Keywords: *Muscle Soreness, Cumulative Charge, Neuromuscular, Pain management, Activation Technology*

Introduction

Individuals exposed to bouts of eccentric muscle exercise experience a short-term inflammatory response (peaking 1 to 3 days post-exercise) that is healed over the period of 1 to 2 weeks.^{1,2} This phenomenon is known as Delayed Onset Muscle Soreness (DOMS).^{3,4} The development of DOMS is

due to the strain experienced by the muscle-tendon unit during eccentric contractions, which causes muscle fibers to incur damage generally in the vicinity of the myotendinous junction. Exposure to such loading conditions typically results in pain, soreness and tenderness, and a significant decrease in force production capacity (thought to be due to sarcomere “popping” and disorganization).¹ DOMS appears to be associated with damage to several structures, including muscle fibers,³ the sarcoplasmic reticulum⁴ and connective tissue.⁵ Individuals who experience DOMS due to repeated eccentric contractions appear to subsequently enjoy a training benefit (a resistance to damage from similar eccentric exertions) that may last up to 6 months. This is sometimes referred to as the “repeated bouts effect”.⁶

Various techniques have been suggested in attempt to relieve the symptoms of DOMS, or to decrease required healing time.⁵ These have included various stretching regimens (pre- and/or post-exercise),^{7,8} use of non-steroidal anti-inflammatory drugs,⁹⁻¹¹ and ice-packs and massage treatments to name a few.^{12,13,19} However, relatively little evidence exists to support the use of such techniques.

Another method that has gained interest in relieving symptoms and potentially improving the healing process is the use of electrical stimulation therapies. The best-known technique has been referred to as transcutaneous electrical nerve stimulation (TENS), or the topical application of variable voltage pulses via skin electrodes with lower frequency levels, often producing a mild pricking sensation. This technique has been widely used by physical therapists, chiropractors, and others primarily as a treatment to control pain¹⁴ and as an attempt to increase the rate of healing.¹⁵ While the use of TENS has shown to be of benefit in the treatment of certain conditions,¹⁶ such treatment by itself or in combination with cold therapy does not appear to have been effective with respect to DOMS.^{17,19}

In this study, the authors sought to examine the efficacy of a new technique of neuromuscular activation in the treatment of DOMS with the Sigma Q® Bioneuro System (Biosysco Holdings Limited, London, UK). Though similar in topical electrode placement as the TENS technique, the Sigma Q® system differs by applying a high-frequency variable voltage series of pulses that produces a cumulative charge and activates neuromuscular deep-tissue muscle contraction. This cumulative charge activation technology

(CCAT) is applied to activate muscle recovery and enhance performance. In published clinical case studies with neuromuscular injury patients, application of this system has demonstrated a marked improvement in patient mobility, lessening of pain, and enhanced rehabilitation¹⁸. While this previous evidence suggests a therapeutic effect, additional research was needed to assess efficacy of this technology in reducing symptoms and facilitating the healing process. Accordingly, the aim of this study was to evaluate whether treatment with CCAT was effective in reducing objective injury measures and subjective pain symptomatology following exposure to an eccentric exercise protocol designed to elicit a DOMS response.

Methods

All procedures used in this investigation were reviewed and approved by Institutional Review Board (IRB). Twelve males and twelve females (24 volunteers total), in the age range of 19 to 30 years, were recruited in accordance with the IRB process, i.e. participants were required to meet inclusion and exclusion criteria to be eligible for the study. Subject demographic data are presented in Table 1. All subjects were in good general health and were required to provide informed consent prior to participation. Subjects who had engaged in eccentric weight training within the prior 6 months or with prior history of arm pain, breathing problems, blood conditions, or other discomfort with phlebotomy procedures were excluded from study participation. Subjects were financially compensated for their participation.

Table 1. Subject Demographic Data

Demographic Data	Overall			Male			Female		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Age (years)	25	3	(20, 30)	27	2.2	(22, 28)	24	2.8	(20, 29)
Height (m)	170	9.2	(154, 189)	177	6.8	(167.7, 189.0)	164	5.2	(154.0, 173.5)
Body Mass (kg)	164	43	(46.49, 112.49)	193	38	(55.79, 112.49)	134	22	(46.49, 77.34)
BMI (kg/m ²)	25	4.6	(18.50, 32.89)	28	4.4	(19.84, 32.89)	23	3.2	(18.50, 28.41)

CCAT TREATMENT SETUP

The CCAT treatment was administered using the Sigma Q® Bioneuro cumulative charge activation device (Figure 1) and active (50mm x 50mm) electrode connectors (Figure 2). This device is an analog-based, multifunctional device designed to be adjustable for timed therapy sessions. There are four output modes. These include combinations of two rhythm generators and wave signal indicators based on positive or negative polarity.



Figure 1. Bioneuro® Unit



Figure 2. Connecting wires and electrodes

Twenty-four subjects were randomly assigned to either an experimental group or a no-treatment control group. Both groups were exposed to an eccentric exercise regimen designed to elicit DOMS on Day 0 of the experiment. The treatment group was provided five Sigma Q® treatments subsequent to administration of the eccentric exercise. These treatments were administered on Day 0 (4 hours post exercise), and on Days 1

through 4 of the 8-day recovery period. The control group was allowed to recover normally (i.e., no treatment was provided). Dependent measures for this study included: 1) subjective responses collected on a wellness questionnaire that included items assessing symptoms and sleep quality; 2) resting elbow angle (a measure of the severity of the DOMS response; 3) serum creatine kinase (a measure of muscle damage); and 4) maximum voluntary isometric contractions (a measure of the damage and recovery of muscles subsequent to eccentric exercise). Independent variables included Group (treatment versus control) and Day (of post-DOMS recovery period). Statistical analysis procedures included analysis of variance (ANOVA) with repeated measures and linear and non-linear regression methods.

Results

OBJECTIVE OUTCOMES

Maximum Isometric Voluntary Contraction

A significant Day and Gender interaction ($F_{5, 100}=4.229$, $p=0.0016$) was observed from the 3-way ANOVA examining factors Treatment, Gender, Day, and interactions. Comparing the 2 genders on individual days, male's MIVCs were significantly greater than female's on all days (Day 0 PRE: $p=0.0015$; Day 0 POST: $p=0.0048$; Day 1: $p=0.0044$; Day 2: $p=0.0074$; Day 4: $p=0.0023$; Day 8: $p=0.0008$). Comparing each gender's MVICs over time, male's MIVCs on Day 0 pre-exercise were significantly greater than Days 0

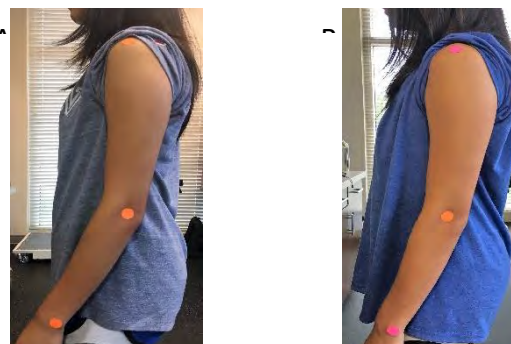


Figure 6. Average REA on (A) Day 0 was 154.5 degrees, and on (B) Day 2 was 158.0 degrees.

post-exercise ($p=0.0002$), 1 ($p=0.0096$), and 2 ($p=0.0212$); male's MVICs on Day 8 were significantly greater than Days 0 post-exercise ($p=0.0002$), 1 ($p=0.0003$) and 2 ($p=0.0013$). Female's MIVCs on Day 0 pre-exercise were significantly greater than Days 0 post-exercise ($p<0.0001$), 1 ($p<0.0001$), and 8 ($p=0.0037$); female's MIVCs on Day 0 post-exercise were significantly lower than Days 2 ($p=0.0432$), 4 ($p=0.0016$), and 8 ($p<0.0001$) (Figure 7A). Overall, MIVCs on Day 0 pre-exercise were significantly greater than days 0 post-exercise ($p<0.0001$), 1 ($p<0.0001$) and 2 ($p=0.0013$); MIVCs on Day 1 were significantly lower than days 4 ($p=0.0005$) and 8 ($p<0.0001$); MIVCs on Day 2 were significantly lower than Days 4 ($p=0.0032$) and 8 ($p<0.0001$); MIVCs on Day 4 were significantly lower than Day 8 ($p=0.0068$) (Figure 7B).

Relaxed Elbow Angle

ANOVA results indicated that Day had a significant effect on REAs ($F_5, 100=20.20$, $p<0.0001$). A trending effect of Day and Gender was observed ($F_5, 100=2.017$, $p=0.0826$). None of the pairwise comparisons between males and females on individual days was significant. (Figure 7D). The

rate of recovery of REA from Day 0 (post-exercise) through Day 8 for both Treatment and Control groups was examined using linear regression. For the Control group, the equation obtained was:

$$\text{REA (degrees)} = 152.1 + 0.2995 * \text{Day}$$

whose slope was not significantly different from zero. Linear regression analysis for the Treatment group generated the following equation:

$$\text{REA (degrees)} = 152.4 + 0.5607 * \text{Day}$$

with a significant slope ($p = 0.0049$). The coefficients of these equations indicate that starting from approximately the same resting elbow angle on Day 0 post-exercise, the treatment group REA recovered at approximately twice the rate of recovery of that experienced by the control group (Figure 7C).

Creatine Kinase

Gender significantly affected CK levels from the results of the 3-way ANOVA ($F_1, 20=8.791, p=0.0077$). Day was a significant factor ($F_1, 22=9.240, p=0.0060$) when non-significant terms were pooled with error. On Day 1, males' CK was significantly greater than females' ($p=0.0177$) (Figure 7E, F).

SUBJECTIVE OUTCOMES

Results of subject perceptions of soreness/stiffness (Figure 8A) from 3-way ANOVA demonstrated a significant interaction of Treatment and Day ($F_5, 100=7.738, p < 0.0001$). Subject reports of Arm Pain also exhibited a significant Treatment by Day interaction ($F_5, 100=2.56, p=0.032$), as shown in Figure 8B.

Subjects' perceived limitations in work and daily activities demonstrated a significant Day effect ($F_5, 100=8.143, p < 0.0001$) and trending Treatment by Day interaction ($F_5, 100=1.940, p=0.0943$) and Gender * Day interaction ($F_5, 100=1.924, p=0.0970$) effects. In the Control group, the rating was significantly lower on Day 0 than Days 1 ($p=0.0282$), 2 ($p=0.0282$), and 4 ($p=0.0463$); Day 8's rating was significantly lower than Days 1 ($p=0.0176$), 2 ($p=0.0176$) and 4 ($p=0.0146$). Finally, subject assessment of sleep quality was found not to be affected by any of the independent variables ($p > 0.05$).

Discussion

Results of this study suggest that the treatment with CCAT demonstrated beneficial effects in both objective and subjective outcomes. Results of the regression analyses of the recovery of the relaxed elbow angle in the treatment and control groups showed a significant slope in REA recovery for the treatment group, but not for the control group. REA is thought to be due to an influx of calcium from the damaged sarcoplasmic reticulum and appears to be indicative of the amount of damage sustained by the affected muscle due to eccentric contractions⁴. Results showing that the treatment groups experienced a faster recovery of the baseline relaxed elbow angle, suggest the possibility that repair to the sarcoplasmic reticulum may be enhanced as a result of the treatments provided. Further research may be necessary

to verify this possibility. However, no treatment effects were observed for recovery of isometric strength or expression of CK.

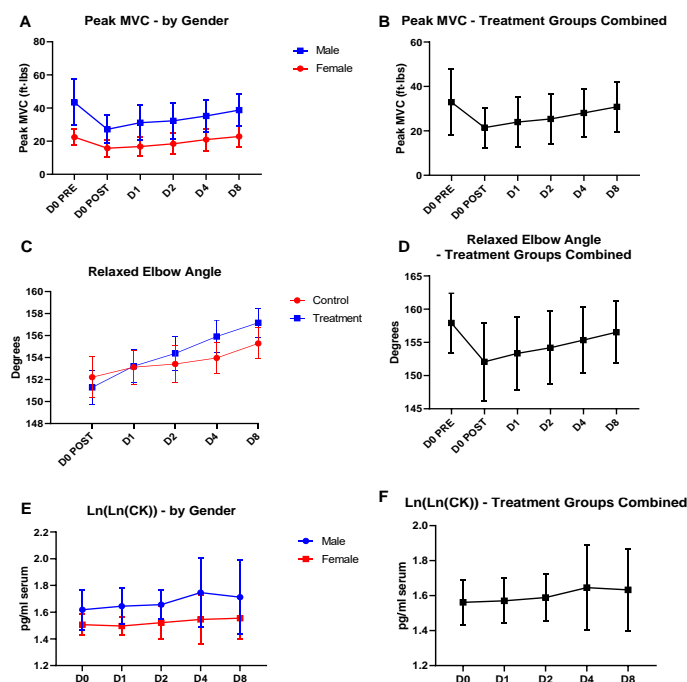


Figure 7. (A, B) Peak isometric MVCs (mean \pm SD) over time. (C, D) Relaxed elbow angle (mean \pm SD) over time. (E, F) Ln-Ln-transformed Creatine Kinase (CK) levels (mean \pm SD) over time.

Treatment by Day interactions in this study suggest remedial effects of the CCAT regarding subjective outcomes (Figure 8), including ratings of arm pain and arm stiffness/soreness. Statistical trends were observed for subjective assessment of limitations in work and daily activities, and physical readiness. It is notable that for all of these subjective measures (shown in Figure 8), the responses of the Treatment group were consistently lower throughout the recovery period compared to the Control Group. It is generally observed that the rating peaked on 1 and 2 days post-exercise and recovered nearing Day 8. There were no adverse outcomes reported by the subjects due to the treatment.

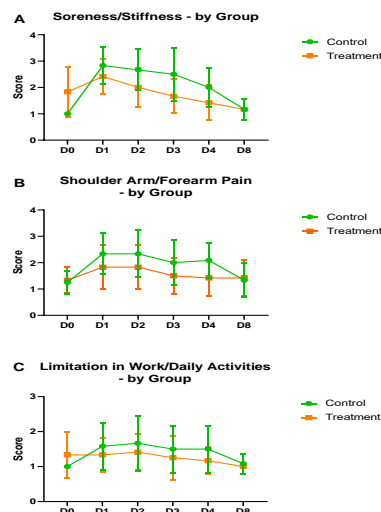


Figure 8. (A) Self-reported rating of soreness/stiffness of the DOMS arm (mean \pm SD) over time. (B) Self-reported

rating of pain of the DOMS arm (mean \pm SD). (C) Self-reported rating of limitations of work/daily activities (mean \pm SD) over time.

All studies have inherent limitations and this one is certainly no different. Gender was observed to be a significant contributing factor of subjective outcomes of this study. The authors therefore suggest subjects with a variety of individual characteristics, such as gender, age and BMI, to be considered in the future and be recruited of sufficient sample sizes in order to gain understanding of the recovery and injury pathways of these sub-populations. While the sample size selected was similar to other studies of this sort, the sample size was somewhat small. This might have affected the ability to achieve significant results for certain measures. Furthermore, because subjects could not serve as their own control in this study (due to the conditioning effect obtained with eccentric exercise), differences between the treatment and control conditions were relatively large. However, this model of injury and repair of musculoskeletal tissues required such a design. Nonetheless, it is noteworthy that several significant differences existed in the pattern of responses for subjective and objective measures between control and treatment conditions. These findings contribute to improving the understanding of CCAT's effect on eccentric-exercise related DOMS.

In conclusion, Sigma Q® Bioneuro-based CCAT treatment resulted in a significant decrease in the self-reported ratings of the symptoms of pain, stiffness, and soreness post-eccentric-exercise. The treatment group demonstrated a significant rate of recovery post-exercise in relaxed elbow angle (REA), nearly twice that of the control group. Overall, treatment with the cumulative charge activation technology displayed substantial measurable improvement in flexibility and functionality recovery as well as considerable reduction in perception of pain post injury with no adverse effects on all measures of recovery.

Acknowledgement

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Stretchable Cable for Mechanically Stable Intraspinal Microstimulation Implants

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Abstract: Helically coiled cables consisting of sixteen microwires were developed in this study. The coiled cables are highly stretchable and retain their electrical properties after experiencing up to 40% of strain. The developed lead system can minimize the effect of relative movement between neural implants and the anchoring points. They are particularly suited for intraspinal microstimulation implants.

Keywords: Stretchable cable, Neural implants, Spinal cord injury

Introduction

Intraspinal microstimulation (ISMS) is a novel approach that directly stimulates the spinal cord locomotor circuits using penetrating electrodes. While ISMS has been very successful in restoring limb movements after spinal cord injury in cats [1], [2], there are some challenges in fabricating mechanically stable implants for large animal models and humans. The main challenge is that the inserted electrodes are prone to movement and/or dislodgment due to body movements[3]. Coiled cables have been used in peripheral nerve and muscle stimulations; they have been shown to be effective in reducing the tissue damage, lead migration, and improving the functionality of the neural interface[4]–[6]. In this study, we propose a helically coiled cable that can interface with ISMS electrodes.

Methods

Coiled leads were fabricated from 25 μ m (Pt-Ir, 80%-20%) microwires insulated with polyimide. Sixteen microwires were bundled and inserted in a Silastic tube (OD: 0.6 mm). The tube was coiled around a 200 μ m Tungsten rod with an approximate density of 25 turns/cm. The tube was then unwound, filled with polydimethylsiloxane (PDMS), and cured at 100 °C. A PDMS tab was incorporated in the Silastic tube that can be used for anchoring the system to the spinal cord (figure 1). Mechanical and electrical properties of the coiled lead was

evaluated by uniaxial tension tests and electrochemical impedance spectroscopy (EIS) tests, respectively.

Results

Figure 2 shows the average load-extension curve of a cable stretched to 40% of strain (n=6). The linear increase in force as the result of extension shows the elastic mechanical behaviour of the cable. Figure 3 shows the magnitude and phase angle of impedance between one microwire in the cable and remaining 15 microwires of coiled leads tested in phosphate buffer saline solution (n=6) both while the cable was at rest and while stretched to 40% of strain.

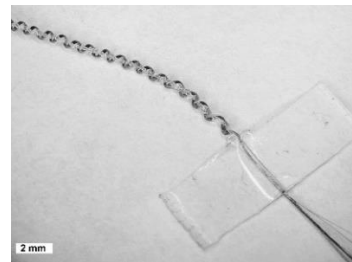


Figure 1. Image of the coiled cable and PDMS tab

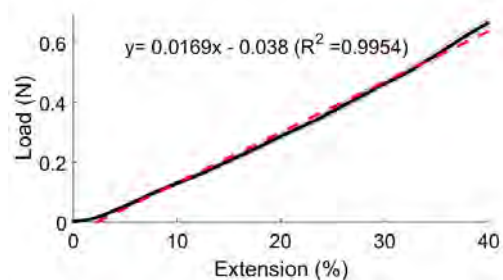


Figure 2. Elastic mechanical behaviour of the coiled cable tested 6 times (shaded area represents standard deviation, dashed line represents linear fit on the mean curve).

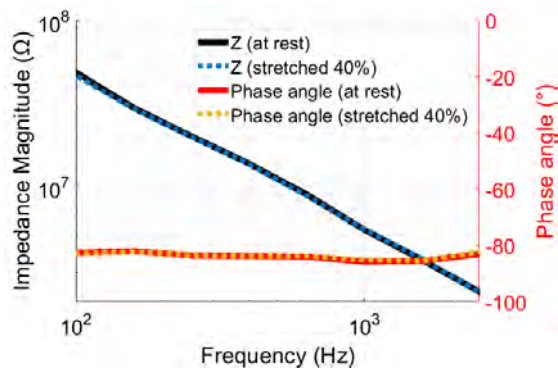


Figure 3. Magnitude and phase angle of the measured impedance as function of frequency and elongation.

Discussion

The developed coiled cable can be connected to 16 micro-electrodes typically used in ISMS implants. The unchanged electrical properties of the coiled cable after applying 40% of strain, demonstrates the mechanical integrity and electrical isolation of leads after elongation. Furthermore, the capacitive impedance shows that there was no crosstalk between individual microwires. The developed stretchable lead system contains 16 microwires and has a very small diameter ($<600\text{ }\mu\text{m}$); it can improve the stability and safety of the implanted ISMS device and other neural implants to reduce the stresses experienced by the implanted electrodes.

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Development of Integrated Multi-Electrode for FES

Using Stretchable Mesh Material to Induce Hand Posture

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Abstract: *This paper presents the proposal of a novel rehabilitation system developed using functional electrical stimulation that can be used routinely in patients suffering from hemiplegia due to central nervous system disorders. In this study, we developed an integrated multi-electrode array that can be easily attached using a mesh material that is sufficiently elastic and tear-resistant to accommodate the physical characteristics of each individual. Through suitable modifications, the wearing time of the proposed multi-electrode array was reduced to one-third that of the conventional array. Moreover, to prove its applicability, in the stimulation experiments, the developed multi-electrode array was used to provide electrical stimulation to five healthy subjects with 125 different stimulation patterns. Hand posture was measured using hand tracking, and the number of hand postures and their respective tendencies were investigated from the results obtained. In addition, we investigated the stimulation positions wherein the five fingers were flexed independently.*

Keywords: *Functional electrical stimulation, Multi-electrode array, Surface electrode*

Introduction

The number of patients with limb paralysis due to cerebrovascular disease (stroke) or after-effects of traffic accidents is increasing annually, with Japan reporting approximately 1.93 million patients in 2016 [1]. It has been found that the rehabilitation of brain-damaged patients can form new neural circuits and enable them to move their limbs again, thereby reducing limb paralysis. Rehabilitation that utilizes the plasticity of the brain is called neurorehabilitation [2]. In particular, neurorehabilitation using functional electrical stimulation (FES) is a rehabilitation technique that uses electrical stimulation of muscles and peripheral nerves to contract them, thereby improving muscle responsiveness. The electrodes used in FES are classified as surface, transcutaneous, and implanted electrodes [3]. The surface electrode method is less burdensome and easier to attach and detach than the implantable electrode method, which requires surgery and places a greater burden on the patient. Therefore, the surface electrode method was adopted in this study. In addition, the location of the motor point (MP), which is highly responsive to muscle stimulation, differs from person to person; therefore, developing a system to estimate the appropriate stimulation location is a challenge. In recent years, research has been conducted on selective stimulation by applying multiple electrodes simultaneously to search for the stimulation position. The purpose of

this study was to develop an integrated multi-electrode with FES for daily use by patients with limb paralysis caused by central nervous system disorders and evaluate the expressed hand posture.

Previous studies

Malešević et al. proposed a method for expressing the grip-opening posture using 33 electrodes. A sheet with 16 electrodes was attached to the ventral and dorsal sides of the forearm, where the ventral side was the anode for grasping, while the dorsal side was the anode for opening. In addition, it was suggested that the grip-opening movement could be expressed, although the index finger movement was difficult to express [4].

Popović-Maneski et al. improved the electrodes developed by Malešević et al. by increasing the number of electrodes per sheet to 24 and widening the stimulation range to focus not only on simultaneous movements but also on movements of each finger and wrist [5]. The size of the electrode sheet cannot be changed. As a result, the size of these electrodes is too large for women and children, and hence, they can only perform a rough search.

Tamaki et al. proposed a method for generating independent movements of each finger using 28 electrodes [6]. Two belts with 14 electrodes attached in a row were worn on the forearm, and experiments were conducted using a combination of 14 sets of stimulation patterns and 12 levels of electrical stimulation magnitude. The results suggested that the index, middle, and ring fingers moved independently without being linked to the other fingers. However, the stimulation position was limited to a part of the forearm, and the search range was narrow.

Further, Kasuya et al. applied 25 independent electrodes in a grid pattern evenly over the entire forearm and investigated the relationship between the stimulation position and complex hand postures such as grip, scissors, and thumbs-up. Furthermore, we proposed an efficient method for deriving the stimulus location that expresses a specific posture [7]. However, certain problems were encountered, such as the time-consuming process of attaching the electrodes manually and the fact that the same stimulation pattern does not always produce the same posture in the second experiment because of the misalignment of the attaching position.

Hatazawa et al. proposed a cylindrical integrated multi-electrode with 25 electrodes evenly distributed on the base of an elastic silicone material, referring to the electrode arrangement by Kasuya et al. [8]. The results showed a reduction of approximately 15 min in the attaching and

detaching time compared to the method of Kasuya et al. and suggested that there was no difference in the hand-evoked performance. However, the silicone material tends to break at the incision, and the thicker the silicone, the heavier the material becomes, and consequently, there is less adherence to the skin.

Therefore, the requirements for the integrated multi-electrode to be developed in this research are expressed in multiple hand postures; these include the single flexion and extension postures of each finger, referring to the electrode arrangement of Kasuya et al, and integrating the multiple electrodes, such that they can be easily attached and detached. In addition, the base of the integrated multi-electrode was designed to correspond to the physical characteristics using a mesh material that is lightweight, difficult to tear, and has elasticity.

Methods

Subjects: The subjects were four healthy males and one healthy female in their twenties. The experiment was conducted on the left hand of all the subjects. This experiment was conducted after approval from the ethical review of the University of Electro-Communications in accordance with the Declaration of Helsinki.

Mesh-based silicone electrode array: The appearance of the developed integrated multi-electrode stimulation array (hereinafter referred to as "silicone electrode array") is shown in Fig. 1. Each of the 25 electrodes had a diameter of 25 mm and a thickness of 1 mm, and the carbon powder was 3% of the total weight when mixed with silicone. The electrodes were 25 mm in diameter and 1-mm-thick. Further, the base was made of silicone sheet filled with silicone in a mesh material made by Tanac Corporation. The mesh material used has a hexagonal lattice structure and a large elasticity in one direction. More-over, it is a material that is difficult to tear and has good elasticity. The silicone electrode array consisted of five legs connected at the base, and each row had five electrodes at equal intervals. Velcro strips are sewn on the wrist and elbow to secure the electrodes in place and prevent them from shifting. The method of attaching it to the left hand is as follows.

(1) First, the band was wrapped around the Velcro on the foot side of the silicone electrode array around the upper arm side of the elbow.

(2) The first electrode was placed on the right side of the ulnar stromal process with the thumb on the upper side, and subsequently, the second to fifth electrodes were placed on the wrist by fixing them with Velcro.

(3) The ulna was placed with a row of silicone electrode array, including 'No. 1' along the right side of the ulna.

(4) The diameter of the elbow was measured, and the remaining four rows were placed such that the diameter was divided into five equal parts.

(5) The electrode was covered with an arm cover to prevent it from shifting.

Electrical stimulation: Electrical stimulation was performed using a stimulator developed in our laboratory [9]. The stimulation waveform was a burst-modulated square wave, which is a high-frequency biphasic square wave modulated by a low-frequency burst wave (Fig. 3). The

voltage used was set for each subject such that the hand posture would be expressed while the pain would be minimal.

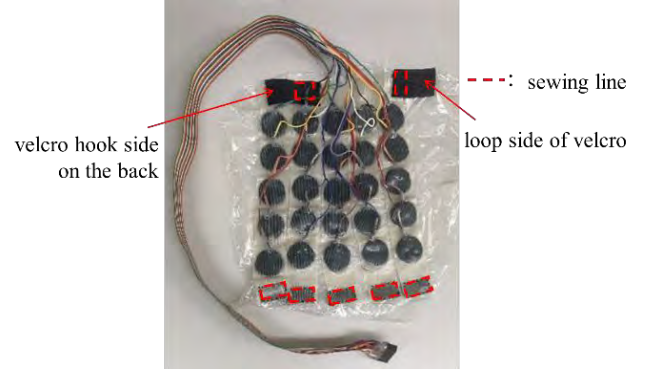


Figure 1: mesh-based silicone electrode array

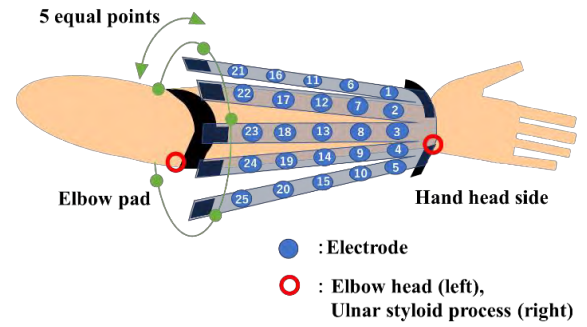


Figure 2: Image of mesh-based silicone electrode array attachment

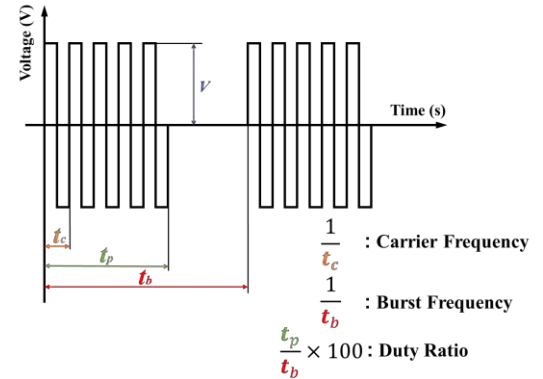


Figure 3: Stimulation waveform

Table 1: Stimulus parameters used in the experiment.

Stimulus parameters	Set value
Burst Frequency	100[Hz]
Burst Duty Ratio	50%
Carrier Frequency	2000[Hz]
Carrier Duty Ratio	50%

Finger joint angle measurement: All 21 xyz coordinates of the fingers, including the fingertips and each joint, were detected using hand tracking from a web camera and output as a landmark list in a csv file. Subsequently, the output csv data were used for angle calculation and flexion-extension discrimination using VBA in Excel. For hand tracking, we used the Mediapipe [10] Python package developed by Google and built the environment in Visual Studio.

Although hand tracking has been reported to have an accuracy of 97.5% [11], it cannot accurately measure the depth of the z-coordinate. Therefore, we first captured the maximum value in extension and the minimum value in flexion of each joint, and thereafter, started measurements to discriminate extension and flexion based on the relative rate of change of joint angles at a certain point. For MCP and IP of the thumb, and MP and PIP of the index to little finger, extension and flexion were determined when the values after flexion or extension changed by 50% from the maximum and minimum values. A single web camera connected to a PC was used to capture the expressed hand posture, and the relative angular change rate of the hand posture detected by hand tracking was used to discriminate flexion and extension simultaneously, simplifying the entire search experiment.

Experimental protocol: In this experiment, the practitioner measured the time required for the subject to wear 25 single electrodes and the time required for the subject to wear the newly developed silicone electrode array. In the stimulation experiment, the subject was stimulated for 2 s and rested for 3 s with 125 different combinations of electrodes. After a 15-min rest, all 125 patterns were explored, and a 15-min rest was performed for a total of three sets. Fig. 4 shows the experiment and measurements.

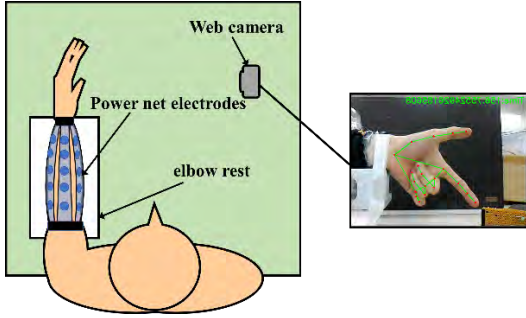


Figure 4: Scene of the experiment and measurements

Experimental results and discussion

The results of the electrode wearing time for the five subjects were 1124.8 ± 51.87 s for 25 single electrodes and 386.4 ± 72.93 s for the silicone electrode array, which reduced the wearing time by approximately one-third.

Table 2 shows the voltages used for each of the five subjects in the stimulation experiments and the number of hand posture types that emerged in 375 trials of 125 patterns \times 3 sets. When each of the five fingers performed rest, flexion, and extension, there were 243 hand postures, or a fifth power of 3. Further, in the experiment, we confirmed that more than 22 different hand postures were expressed in all subjects, and the total number of hand postures expressed by five subjects was 69. Table 3 shows the top 10 hand postures with the highest number of occurrences excluding no change, and Fig. 6 shows the number of occurrences of these postures by each subject.

Fig. 7 shows the number of times the five fingers were bent independently for each subject. The position of the center of gravity of the four selected 2×2 electrodes was calculated by replacing the coordinates of the 25 electrodes

(5×5) arranged in a grid with spatial coordinates of a cylinder. Since the stimulation waveform used in this study is biphasic, the cathode and anode are mutually switched during the stimulation. Therefore, the midpoint of the two center-of-gravity coordinates of the cathode and anode selected at the start was used as the center-of-gravity of the entire electrode (Fig. 5). Fig. 7 shows that the thumb flexed alone in four out of five subjects, and the total number of observations was 14, which was the 21st out of the total 69. The index finger flexed alone in 2 out of 5 subjects, and the total number of times it was observed was 8, which was the 30th out of the total 69. Considering Nos. 4 and 7 of Fig. 6, it can be observed that the middle and ring fingers flexed independently in all subjects. This suggests that the muscles of the thumb, index finger, and little finger are difficult to stimulate, or they are easily stimulated with muscles of neighboring fingers. In addition, Fig. 8 shows that the distribution of the center of gravity of the electrode for the flexion of the thumb, index finger, and little finger corresponds to the flexor digitorum profundus, flexor digitorum longus, and flexor carpi radialis of the finger flexor group, respectively.

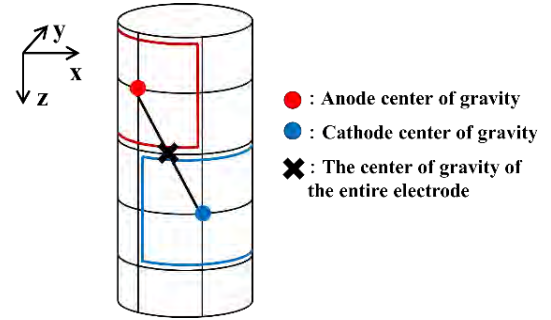


Figure 5: Scene of the experiment and measurements

Table 2: Number of types of stimulus voltage and expressed hand posture for each subject.

	SubA	SubB	SubC	SubD	SubE
Voltage (V)	6.14	5.2	7.09	7.32	4.96
Number of posture types	27	22	35	52	25

Table 3: Top 10 hand postures with the highest number of expressions among the 5 subjects (the second line shows the resting state of flexion and extension from thumb to little finger, where 0 indicates rest, 1 indicates flexion, and -1 indicates extension).

No.1	No.2	No.3	No.4	No.5
0,0,1,1,0	0,0,1,1,1	0,0,0,0,-1	0,0,0,1,0	-1,0,1,1,1
No.6	No.7	No.8	No.9	No.10
0,0,0,-1,0	0,0,1,0,0	0,-1,0,0,0	-1,0,1,1,0	0,1,1,1,1

Conclusion

In this study, we developed a silicone electrode array that can be easily attached using an elastic mesh material and can respond to physical characteristics. Compared to the conventional method of attaching electrodes, the time required to attach the electrodes was reduced to approximately one-third using the developed silicone electrode array, which simplified the preparation for electrical stimulation rehabilitation and reduced the burden on the practitioners and subjects. The results of the stimulation experiments using silicone electrode array showed that more than 22 different hand postures were expressed by each subject, and thus by evaluating the hand postures expressed in the stimulation experiments of five subjects, we could show the hand postures that were easily expressed. Similarly, the coordinates of the center of gravity of the electrode were obtained from the electrode arrangement when each finger was bent independently in five subjects, and a 50% stochastic ellipsoid was created for each finger.

In the future, we will derive a relationship between electrode patterns, and hand posture that is common to more subjects and develop a method to identify the stimulus patterns that express the target posture more efficiently and within a shorter span of time than that of the current total search method. This will enable us to realize a motor function recovery system for the forearm using integrated multi-electrode.

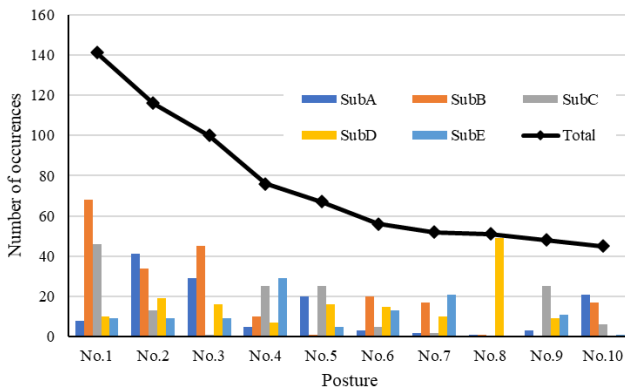


Figure 6: Number of times each subject expressed each posture for the top 10 hand postures with the highest number of occurrences and the total number of all subjects.

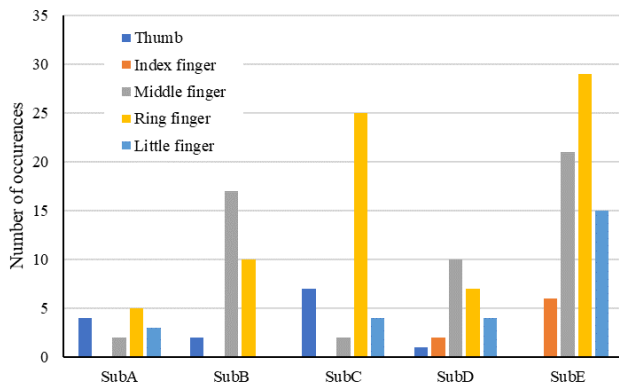


Figure 7: Number of times each subject flexed each finger independently.



Figure 8: Correspondence between the distribution of the center of gravity of the electrode and the forearm when the finger is flexed alone.

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SKELETAL MUSCLE WEAKNESS IN POST-COVID PANDEMIC SYNDROME: ROLE FOR FULL-BODY IN-BED GYM AND FES

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Abstract: People suffering from systemic neuromuscular disorders or chronic organic insufficiency spend little time for daily physical activity, aggravating their motor difficulties. From 2020, patients at risk are also those who, despite being negative for SARS-COV 2 infection, suffer from COVID-19 chronic stress syndrome, specifically fatigue syndrome [1-4]. In addition to any psychological management, it may be useful to offer those patients exercise rehabilitation training that is easy to learn and take home. Inspired by the proven capability to recover skeletal muscle contractility and strength by home-based volitional exercises and functional electrical stimulation (FES), we suggest for chronic COVID-19 fatigue syndrome a 10–20 min long daily routine of easy and safe physical exercises that may recover from muscle weakness the main 400 skeletal muscles used for every-day activities. Leg muscles of frail older patients could also be trained by additional functional electrical stimulation (FES) using co-contraction concentric or moderate-load eccentric exercise. Many of the exercises can be performed in bed (Full-Body in-Bed Gym), so hospitalized patients can learn this light workout before leaving the hospital. Full-Body in-Bed Gym is an extension of well-established cardiovascular-ventilation rehabilitation training performed after heavy surgery. Blood pressure readings, monitored before and after daily routine of Full-Body in-Bed Gym, demonstrate a transient decrease in peripheral resistance due to increased blood flow to major body muscles. Continued regularly, Full-Body in-Bed Gym and FES may help maintaining independence of frail people, including those suffering with COVID-19 fatigue syndrome.

Keywords: skeletal muscle weakness, home-based Full-Body in-Bed Gym, older olds, borderline mobility impaired persons, chronic COVID-19 pandemic syndrome

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DESIGN OF MULTI-PAD ELECTRODES FOR MULTIMODAL ELECTROTACTILE FEEDBACK FROM SUPERNUMERARY LIMBS

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Abstract: We present a multi-pad electrode for providing haptic feedback from a supernumerary robotic limb. Electrode was custom designed to be a multi-modal information channel that can present proprioceptive and sensory information from supernumerary limbs to the user. Electrode was envisioned to be worn on the thigh and to consist of 32 independently selectable channels. Within two pilot tests we investigated return electrode configuration and active electrode discrimination to select the appropriate electrode pad arrangement and topology. Three healthy volunteers participated in these tests. Based on result of these tests and anthropometric data from literature, electrode was designed to have 37.9 cm transverse length and consist of three branches of 10 pads stretching across 15 cm longitudinally. Two additional pads that can be simply displaced over or under the electrode branches are envisioned to present alerts. The electrode is designed to be connected to stimulation system that allows full multiplexing so that specific branches can be used as return electrode. We believe that proposed design will allow users to intuitively interpret proprioceptive and sensory feedback from supernumerary limbs.

Keywords: Electrotactile stimulation, multi-pad electrode, proprioceptive feedback, supernumerary robotic limb

Introduction

Supernumerary robotic limb (SRL) represents a wearable robotic system that should allow humans to perform tasks that are impossible to perform with natural limbs alone. One of the important aspects of the SRL is to provide real-time feedback to the user. However, feedback in SRLs is still not sufficiently explored and most of the results are related to the sixth finger, including both vibrotactile [1]-[3] and electrotactile feedback [4],[5]. Nocco et al. investigated a system that provides the user with proprioceptive feedback from a SRL, using four vibromotors placed on the subject's leg [6].

Lower limbs are one of preferred sites for the electrode placement because it can be assumed that this will avoid interference with natural proprioception from upper limbs controlling the SRL, especially in complex applications such as tri-manual manipulation or three-tools surgical assistance. Vibrotactile or electrotactile feedback delivered to lower limbs is commonly used in closed-loop control. Most of the presented systems rely on one or two vibromotors placed on different parts of the leg [7]-[10]. Chen

et al. used six vibro-motors distributed on anterior and posterior side of the thigh [11]. Plaque et al. used eight vibro-motors equally spaced along the circumference of the thigh [12]. According to Wentink et al., the best position to provide tactile feedback appeared to be the medial and posterior side of the upper leg [13]. Higher resolution can be achieved when using transverse orientation in factor spacing in comparison to the longitudinal orientation [14].

Research investigating electrotactile feedback on the lower limb in closed-loop systems was mostly directed towards single-channel systems [15],[16]. The thigh is the most common site for the electrode placement, especially medial side and transverse ring around the thigh [17]-[19]. Vos et al. used an electrode array with eight channels and showed that it was a preferred number, but emphasized that hardware limitations were a key reason for not exploring a higher number of channels [17]. Electrotactile feedback has many benefits: it is inexpensive, it has no mechanical or moving parts and it can deliver a wide variety of sensations to the user by simply varying the electrical signal delivered to the electrodes [20]. Different information coding can be achieved with satisfactory discrimination accuracy by modulating the following stimulation parameters, independently or combined: stimulation duration, number of activated channels, site, pulse width, frequency and amplitude [5],[21]. This approach was previously used for successful restoration of proprioceptive and interaction force feedback from myoelectric prosthesis [22]-[25].

This paper presents the process of designing a custom electrode for providing electrotactile feedback from SRL to the lower limb. Pilot psychometric tests were performed to evaluate feasibility of the proposed electrode positioning and select suitable electrode configuration. Based on these findings, a multi-array electrode with 32 pads distributed circumferentially around the thigh was designed.

Methods

Two pilot tests were performed in order to determine suitable active and return electrode configurations for the desired application and positioning. Hereafter, "active electrode" denotes a pad intended to produce tactile sensation, while the "return electrode" denotes a group of pads selected to close the electrical circuit without eliciting sensations. The first test aimed to determine the return

electrode configuration, i.e., the number of pads that would provide sensation localized below the active pad. Additionally, this test examined the effects of size, shape and distance of return electrode pads on current flow localization and discrimination of individual pads. Based on the results of the first test, the active electrode discrimination test was conducted to explore the spatial resolution, i.e., the subjects' ability to discriminate individual positions of two pads at different distances. Finally, the multi-pad electrode was designed based on the obtained results and literature survey on the anthropometric data, i.e., average thigh circumferences and lengths.

Subjects

Three healthy subjects (two females and one male, aged between 23 and 25 years) participated in the study. The subjects were provided with an information sheet and signed an informed consent form. The study was approved by the ethics committee of University of Belgrade - Faculty of Medicine, Belgrade, Serbia.

Setup

Four designs of 16-pad electrode arrays with different pad sizes and pad-to-pad distances (Tab. 1) were used for delivering electrotactile stimulation. Electrode pads were covered with conductive hydrogel (Axelgaard, DK) to improve the electrode-skin contact. The charge-balanced biphasic pulses were generated by the current-controlled stimulation unit (Tecnalia R&I, ES) that was Bluetooth controlled through a LabView (National Instruments, USA) application. The frequency and pulse width were constant during the experiment and set to 30 Hz and 300 μ s, respectively, while the amplitude was adjusted for individual configurations during the tests.

Table 1: Specifications of the four multi-pad electrodes used in the experiment

Electrode design	Pad shape	Pad dimension	Edge to edge distance
I	circle	Diameter 1 cm	0.9 cm
II	rectangular	1.7 cm x 1.5 cm	0.4 cm
III	rectangular	1.4 cm x 2.9 cm	0.3 cm
IV	rectangular	1.1 cm x 1.9 cm	0.3 cm

Protocol

The subjects were comfortably seated on a chair and two electrode arrays were placed on their right thigh. Pads of the first electrode array, placed on the middle of the anterior side of the thigh, were used to form the return electrode. The other array, used to select active pads, was positioned 7 cm above (centre-to-centre distance). Stimulation unit was placed over the electrodes on the leg and fastened with a stretchable strap.

Return electrode configuration test: Six return electrode configurations were tested for each electrode design. Protocol scheme is shown in Fig. 1, where the first row (coloured blue) represents upper electrode array, where only one pad was activated in all six configurations. The remaining rows (coloured grey) represent different return electrode configurations: 1) eight pads, 2) five pads, 3) three neighbouring pads, 4) three pads with a single-pad

gap, 5) three pads with two-pad gap and 6) one pad. The subject gradually increased the stimulation amplitude with a 0.1 mA step until reaching a comfortable sensation localized below the active pad for the first return electrode configuration no.1 comprising eight pads. The same amplitude was used for remaining return electrode configurations for the same electrode design. Subjects were asked to report whether 1) quality and 2) localization of sensation for remaining return electrode configurations (i.e., no. 2 – 6) are the same as for the first configuration or not (better/worse). The same procedure was performed for all four electrode designs.

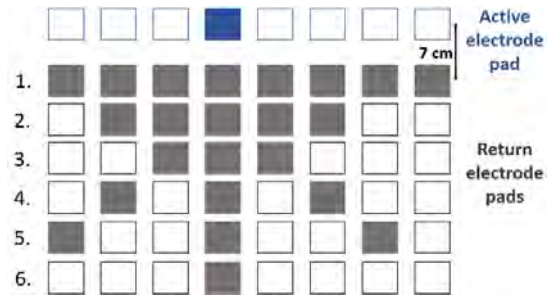


Figure 1: Protocol scheme – return electrode configuration

Active electrode discrimination test: Three active electrode configurations were compared using Electrode I design (Tab. 1) in order to investigate the spatial resolution of electrotactile stimulation on the thigh and the subjects' ability to discriminate between two pads. The configurations comprised two pads with different gaps between them: 1) 4-pad gap with 4.9 cm edge-to-edge distance, 2) 3-pad gap with 3.7 cm distance and 3) 2-pad gap with 2.5 cm distance. The return electrode always consisted of five pads (configuration no. 2 from return electrode configuration test). Protocol scheme is shown in Fig. 2. Both active pads were separately calibrated by gradually increasing the stimulation amplitude with a 0.1 mA step until reaching a comfortable sensation localized below them. Following the calibration, two electrode pads were activated randomly, and the subjects were asked to identify the active pad (left or right) or report if not sure. The subjects didn't receive any training prior to the test nor feedback on the correct answer during the test. The test included ten trials for each of three active electrode configurations.

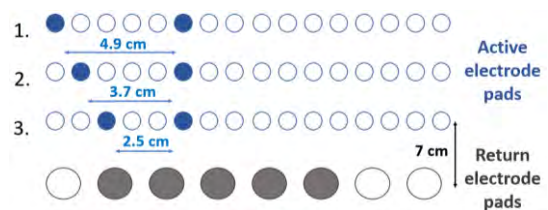


Figure 2: Protocol scheme – active electrode discrimination

Results

Pilot tests

Return electrode configuration test: For all three subjects and four electrode designs, localization of the perceived stimuli was the same for return electrode

configurations no. 1 and no. 2, and significantly worse for configuration no. 6. For return electrode configuration no. 3, sensations were localized for two subjects for majority of tested electrodes. However, some electrode designs (Electrode III for one subject and Electrode IV for the other) produced sensation that couldn't be localized as well as with five and eight pads configurations. For the third subject, the sensation wasn't localized for any electrode with return electrode configuration no. 3. When return electrode configuration no. 4 was used, all subjects felt the localization of the active pad the same as with the eight pads, except for two electrodes (Electrodes I and II) in the case for one subject. The quality of sensation was lower only for one subject and Electrode II. For the return electrode configuration no. 5, all subjects reported the same localization of the active pad as for eight pads (except for the Electrode III in the case of one subject), although the quality of sensation was lower for two subjects with two different electrodes (Electrodes II and IV). One subject reported that the perceived sensation was the most pleasant with the Electrode I, while the other two had no preferences. Current amplitudes ranged from 1.6 mA (subject 2, electrode I) to 7 mA (subject 3, electrode II).

Active electrode discrimination test: All subjects showed 100% recognition accuracy between two active electrodes in all three tested configurations. Therefore, it is possible to reliably discriminate two active pads even at the smallest of the proposed distances. Current amplitudes were similar for all subjects and pads, ranging from 2.0 mA to 2.6 mA.

Electrode design

Custom designed multi-pad electrode with labelled dimensions and distances between pads, as well as the proposed electrode positioning are shown in Fig. 3. The electrode consists of three arrays of ten circle-shaped pads and two additional square-shaped pads which provide flexibility in placement, resulting in 32 pads in total.

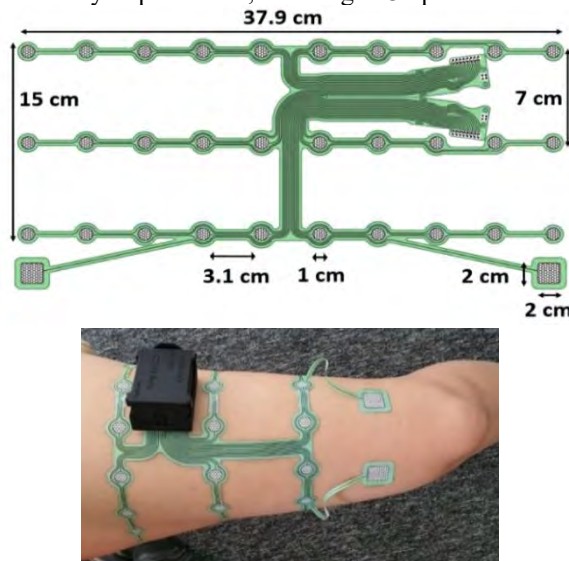


Figure 3: Technical drawing of the custom designed multi-pad electrode for electrotactile stimulation (top) and its placement on the thigh (bottom).

Edge-to-edge distance between the pads in a single electrode array is 3.1 cm and adjacent arrays are vertically separated with 7 cm centre-to-centre distance. Circle-shaped pads are 1 cm in diameter and square-shaped pads are 2 cm x 2 cm. The middle electrode array is placed on the middle thigh and the electrode can be rotated in two ways, depending on the use of two additional pads.

Discussion

The results of return electrode configuration test suggest that similar sensation of localization can be achieved with all return electrode configurations except for the one when only one pad is used to form the return electrode. When comparing return electrode configurations with three pads, configuration no. 4 and 5 proved to be better than no. 3. Return electrode configuration no. 2 and Electrode I were selected for the subsequent active pad discrimination test, because all three subjects reported pleasant and localized sensation with this configuration. The results of active pad discrimination test showed that it is possible to discriminate two pads at all tested edge-to-edge distances (i.e. 4.9 cm, 3.7 cm and 2.5 cm) with 100% recognition rate. This suggest that novel multi-pad electrode could include an array of pads placed transversally around the thigh with at least 2.5 cm edge-to-edge distance between the adjacent pads. It should be noticed that the pilot tests were performed only once, but it could be expected that the main difference would be in the current amplitude values since electrotactile interfaces require calibration prior each use [26].

Our goal was to design the 32-pad electrode which can fit to an average thigh circumference, with maximal possible number of pads in a single array arranged in accordance with the results of pilot tests. Based on the literature, values of thigh circumference range from 46 cm to 61 cm, with an average of approximately 53 cm [27]-[30].

Taking everything into account, it has been decided to design the electrode from Fig. 3, comprising ten equidistant pads with edge-to-edge distance of 3.1 cm. The dimensions were chosen in order to overcome the problem of inter-subject variability. The electrode occupies 37.9 cm, which is 82.4% of the smallest (46 cm), 71.5% of the average (53 cm) and 62.1% of the largest (61 cm) thigh circumference found in the literature. Three electrode arrays occupy 15 cm vertically with 7 cm centre-to-centre distances between the adjacent electrode arrays. This distance of 7 cm is in accordance with the vibrotactile configuration previously investigated by Chen et al. [11]. Two additional pads of larger dimensions were added in order to have an additional alert information channel, which can warn the subject in critical situations that are yet to be defined for specific applications. The position of these two pads is for this reason partially adjustable.

The first step of the future work will include defining the haptic feedback via the developed electrode that can intuitively convey proprioceptive and sensory data from SRL. Subsequently, the developed electrotactile interface will be used to define dynamic patterns for providing intuitive feedback and closing the loop with these additional limbs.

Acknowledgement

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FORCE-CONTROLLED FUNCTIONAL ELECTRICAL STIMULATION FOR GRIP ASSISTANCE AND REHABILITATION

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Abstract:

Functional electrical stimulation (FES) can fulfil the role of an assistive technology and a rehabilitation intervention for people with reduced hand motor control after stroke. Our primary aim was to develop and evaluate a model-based FES controller for power grasp force modulation. The model-based FES controller has a feedforward (FF) component modelled using a Hammerstein structure and a feedback (FB) component. Ten able-bodied subjects completed a set of force-tracking experiments using three control modes, FF-only, FB-only, and FF-FB, in two conditions, without and with voluntary effort. The goodness of fit achieved with the implemented Hammerstein model was $38.7\% \pm 8.7$. Without voluntary effort, the FF-FB (NRMSE: 0.27 ± 0.07 , $p < 0.004$) and FB (0.28 ± 0.04 , $p < 0.004$) controllers performed significantly better than the FF controller (0.32 ± 0.09). With voluntary effort, subjects performed complex tasks better with the FB controller (0.16 ± 0.04) than with the FF controller (0.22 ± 0.06 , $p < 0.01$) and without FES (0.18 ± 0.05 , $p < 0.01$). This work demonstrates the utility of model-based closed-loop FES controllers for grip assistance and rehabilitation.

Keywords: *Functional Electrical Stimulation, Grip Force, Control, Assistive Technology, Hand Rehabilitation*

Introduction

Globally stroke is a leading cause of long-term disability [1]. In the UK there are over 1.2 million stroke survivors and about 80% have a reduction in motor control [2]. The reduced level of movement causes changes in muscle, connective and neural tissues resulting in secondary problems, including paresis, spasticity, pain and lost connectivity in unused neural pathways [3]. In particular, the loss of precise regulation of grip force, which is required for object manipulation, affects many activities of daily living (ADLs), such as feeding, dressing and grooming [4]. This has a devastating effect on the independence, anxiety and quality of life of a person [5].

Functional electrical stimulation (FES) can be used for motion assistance or rehabilitation by activating muscles such that coordinated limb movements are generated, using patterned and temporally sequenced electrical stimulation. Neural synapses can be strengthened by synchronizing voluntary muscle activation and electrically stimulated muscle

activation, leading to neuroplastic changes and restoration of function [6]. However, medically-certified FES devices used in the clinic for hand rehabilitation trigger muscle activation in an on-off manner [7], which can severely limit the utility of FES. Instead, the intensity of stimulation should be varied throughout the everyday activity or rehabilitation exercise to assist only when needed and to provide error feedback that encourages the user to continuously modulate their voluntary grip force. We aim to develop and evaluate FES controllers that modulate grip force and provide neural feedback during task execution to generate evidence of their utility in hand rehabilitation.

Feedforward control of FES

Model-based controllers may be more advantageous than on-off FES systems because they account for nonlinearities in muscle dynamics and allow the level of muscle activation to be controlled throughout task execution [8]. The models used for FES control can be divided into two types: physiological models and empirical models. The physiological models, such as the Hill model or Riener model, tend to be accurate, complex, and subject specific [9]. These models provide a better understanding of the underlying physiological processes. However, the anatomical and physiological parameters of these models are difficult to measure, such as muscle and tissue geometry and conductivity. Empirical models, such as Hammerstein structures or artificial neural networks (ANNs), aim to model the input-output of a muscle but their structures reflect the physiology of muscles less directly [9]. The input-output data required for empirical model identification is acquired by stimulating a muscle with a known signal and recording the output with a sensor during a calibration procedure. This may be more appropriate for FES controllers that are to be used in a rehabilitation clinic or as an assistive device where shorter set-up procedures and fewer expensive devices are desirable.

Feedback control of FES

To account for the time-varying muscle dynamics and to generate more functional movements, various feedback control strategies based on joint angle, position, force, and myoelectric activity have been developed. In finite state controllers [10], functional activities are represented as a sequence of movement phases. Transition into the next phase is initiated by an intent-detection signal, such as one

detected by inertial sensors attached to a limb. However, within a movement phase the controller is still only feed-forward. Proportional-integral-derivative control (PID), sliding mode and fuzzy controllers have been proposed for the control of FES. The majority of these controllers have been trialled for arm or leg rehabilitation [11]. Model predictive and iterative learning controllers have been proposed for object grasp and release using finger position feedback [8] and Westerveld et al. developed a feedforward and feedback thumb force controller [12] using a second order linear dynamic model and PI controller. Few control strategies and models rely on force as a control signal and most have not been designed or evaluated on power grasp force control, yet force acquisition can be inexpensive and quick to set up and grip force modulation is essential to object manipulation.

Aims and Objectives

The aim of this research was to assess the performance of a feedforward controller combined with a feedback controller for power grasp force modulation. An empirical muscle model was identified, and the performance of the feedforward and feedback controllers were evaluated with able-bodied participants. Experiments were conducted without voluntary effort and then with voluntary effort, considering the importance of synchronizing voluntary effort and stimulated muscle activity during FES-assisted stroke rehabilitation. The open-loop model-based controller with reduced gain is hypothesized to increase trajectory tracking accuracy through muscle cueing. The feedback controller is hypothesized to increase accuracy by minimizing tracking errors. A potential application of these controllers is to reduce the difference in skill level between players of multiplayer rehabilitation games (i.e. a patient and their therapist), which allows for increased participation and enjoyment by all players [13].

Methods

Participants

The experiment was approved by the Research Ethics Committee of Imperial College London and was conducted with 10 able-bodied participants (6 women, 23.2 ± 1.7 years old, all right-handed, forearm circumference 20.6 ± 2.1 cm). Each subject was informed about the experiment, gave informed consent, and completed the Edinburgh Handedness Inventory before the experiment.

Controllers

The goal of the FES controllers was to modulate power grasp force, by varying the pulse width of a constant amplitude electrical stimulation pulse train, to track reference force trajectories. Fig. 1 shows the proposed controllers. A Hammerstein structure was chosen as the inverse musculoskeletal model for the FF controller as it is easier to identify than physiological models and requires fewer parameters to identify than ANNs. The Hammerstein model is an empirical model that consists of a static non-linear model (f) and a dynamic linear model (G), analogous to static non-linear muscle fibre recruitment and linear muscle activation dynamics. The FF model was identified anti-causally

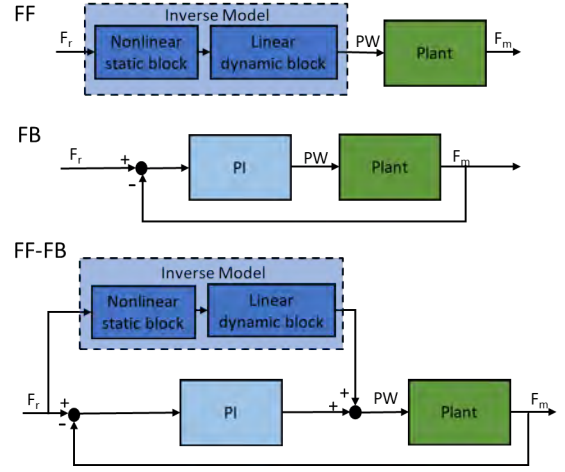


Figure 1. FES-assisted grip force control schemes evaluated. The feedforward (FF) control block uses a Hammerstein structure, and the feedback (FB) control block uses a PI controller. Ramp, sinusoidal and complex force trajectories were used as the reference force (F_r) and the grip force sensor output was used as the measured force (F_m).

for control, with the grip force (F) as the input to the model and the stimulation pulse width (PW) as the output. The non-linear function, the model order and the time-shift operator (q) were chosen experimentally during preliminary tests. The model parameters were identified for each participant using the MATLAB system identification toolbox. The input-output data needed for system identification was recorded during calibration prior to the experiments.

$$PW_{FF}(t) = f(F(t))G(q) \quad (1)$$

Proportional-integral (PI) control was used for the feedback controller (FB). PI controllers output a control signal that is a linear combination of an error signal and the sum of the past errors. The error signal was obtained by taking the difference between the reference force trajectory (F_r) and the measured force trajectory (F_m). The control signal was the stimulation pulse width. The gain parameters, K_p and K_i , were tuned empirically based on observation during preliminary tests to enhance performance.

$$PW_{FB}(t) = K_p \cdot e(t) + K_i \cdot \int e(\tau) d\tau \quad (2)$$

$$e(t) = F_r - F_m \quad (3)$$

The feedforward-feedback (FF-FB) controller combined the FF and FB strategies described above by summing their outputs (4).

$$PW_{FF-FB} = PW_{FF} + PW_{FB} \quad (4)$$

Experimental set-up

Each participant was seated with the forearm of their non-dominant arm resting on a foam cushion on a table. The Tecnia CLASS V1 FES multi-electrode array, which has a hydrogel layer between the electrodes and skin to improve conductivity, was secured in place with Velcro straps and applied stimulation to the flexor digitorum superficialis (FDS). A 20Hz biphasic current pulse, at a constant

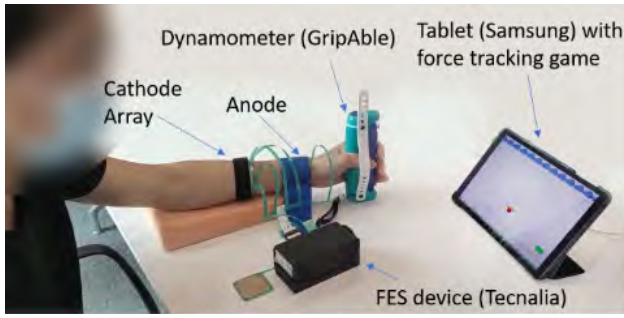


Figure 2. The experimental setup consists of a multielectrode FES array, a grip force sensor, and a tablet screen displaying the reference force with a red ball and the measured force with a yellow line.

amplitude and variable pulse width, was selected since this stimulation frequency is commonly used in rehabilitation and the system has finer resolution in pulse width than amplitude. The FES device's pulse width lower saturation limit is $100\mu\text{s}$, the upper saturation limit is $400\mu\text{s}$, and the precision is $10\mu\text{s}$. Grip force was acquired at 60Hz with a digital dynamometer (GripAble) connected by Bluetooth to an Android tablet (Tab A, Samsung). The FF, FB and FF-FB controllers were implemented in Simulink (MathWorks) and operated at 20Hz to match the stimulation frequency. The Simulink model operated on a personal computer (MobileStudio, Wacom) and synchronized the system by simultaneously sending the reference grip force trajectory through user datagram protocol (UDP) to the tablet, recording the measured grip force sent by the tablet through UDP and sending the computed stimulation pulse width to the FES device through Bluetooth. Fig. 2 shows the experimental setup. A target tracking game developed using the Unity game engine was presented to the participant on the tablet only during tasks that required voluntary effort. The tablet screen displayed the vertically moving reference force with a red ball and the measured force with a yellow line.

Experimental protocol

The electrodes were placed on the forearm of the participant's non-dominant hand. The anode was placed on the dorsal side of the wrist and the 15-electrode cathode array was placed at $40\% \pm 7.0$ of the length of the forearm measured from the wrist. The cathodes were sequentially activated for a 2 second duration at a 6-11mA amplitude based on user comfort, and the cathode that generated the highest grip force without causing discomfort was selected. With the appropriate electrode selected, the stimulation amplitude was increased in increments of 1mA up to the subject's pain threshold. The rest of the experiment was performed at up to 1mA below their pain threshold (A_{Max}). The experiment was divided into three phases: a *calibration* period and a *passive* task where the participant was asked not to exert any voluntary effort and an *active* task where the participant was asked to use voluntary effort to complete the tracking tasks to the best of their ability. For calibration, electrical stimulation was applied in a 3s on 2s off pattern with the stimulation pulse width increasing in $30\mu\text{s}$ increments from $100\mu\text{s}$ to $400\mu\text{s}$ and was repeated ten times.

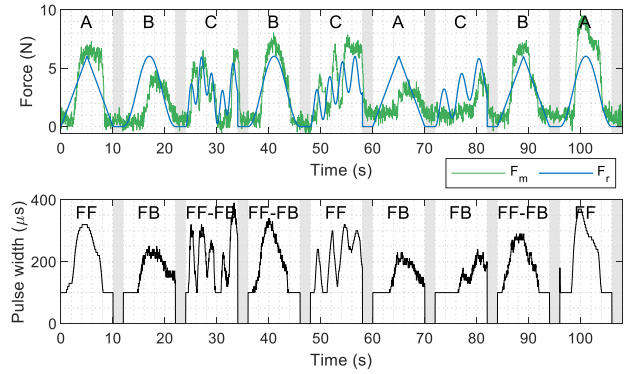


Figure 3. The reference force trajectory (blue), measured force (green), and controller's pulse width output (black) for all controller-trajectory combinations tested during the passive task, using data from participant 7.

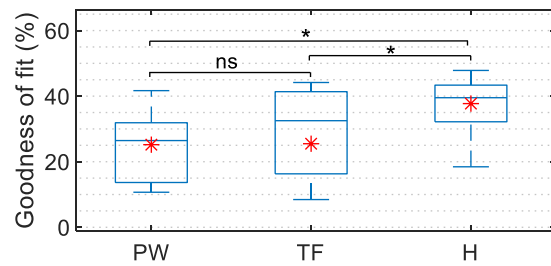


Figure 4. The Goodness of Fit of the Hammerstein (H) model and its piecewise linear (PW) and non-linear transfer function (TF) components, as calculated using ten-fold cross validation on the calibration data.

The measured grip force and pulse width were used as the input and output data for the model's parameter identification and the maximum grip force measured (F_{Max}) was used to set the maximum reference force in the passive and active tasks. During the passive task all combinations of three desired force trajectories, a triangular waveform (A), a sinusoid (B) and a mixed sinusoid (C), and the FF, FB and FF-FB controllers were alternated (Fig. 3). Each trajectory had a 10s duration and ranged between 0 N and F_{Max} . Between each trajectory there was 2s break during which no FES was applied. During the active tasks all combinations of the three desired force trajectories and three control types (FF, FB and No-FES) were alternated. The participants were not informed of the different controllers being trialed. Subjective feedback was collected using the NASA Task Load Index (NASA-TLX) and fatigue and comfort questionnaires (rated from 1-10) to preliminarily assess the effects of prolonged closed-loop stimulation on user fatigue and comfort and the system's usability.

Results

Model

The Hammerstein model's goodness of fit is more accurate than for its piecewise linear ($p < 0.004$) and fourth order transfer function ($p < 0.002$) components alone (Fig. 4). The first ($p < 0.01$) and second ($p < 0.05$) calibration repetitions were significantly different from the following repetitions that correlated strongly with each other.

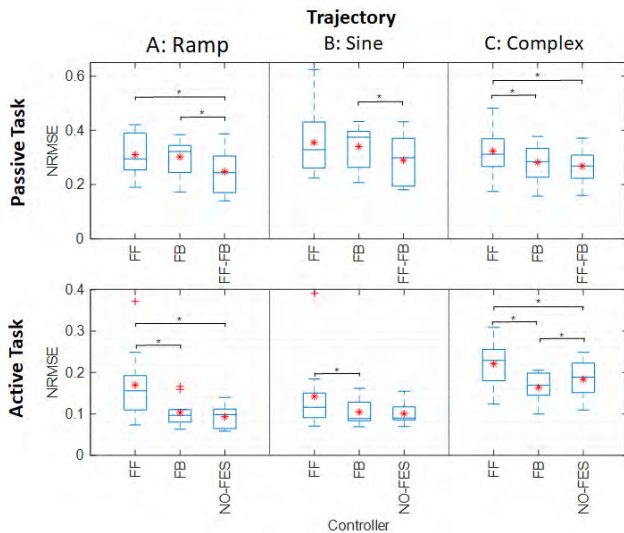


Figure 5. The accuracy of the FF, FB and FF-FB controllers during the trajectory A, B, and C trajectory tracking tasks for the (top) passive and (bottom) active tasks. For reference, if the measured force was zero the NRMSE for trajectory A and B is 0.5 and for C is 0.5013.

Accuracy

The normalized root-mean-square error (NRMSE) over all participants and trials for each passive and active task and trajectory-controller combination is shown in Fig 5. For the passive tasks, the accuracy of the FF-FB controller was higher than that of the FF and the FB controllers for trajectory A ($p < 0.004$). For trajectory B, the accuracy of the FF-FB controller was higher than the FB controller only ($p < 0.01$). For trajectory C, the FF-FB and FB controllers were more accurate than the FF controller ($p < 0.004$). No correlation was found between the participants' goodness of fit and their NRMSE during FF trials.

The active tasks showed higher accuracy than the passive tasks at each trajectory for both control modes. Trials with the FB controller were more accurate than with the FF controller for all trajectories ($p < 0.04$). Trials with the FB controller were more accurate than No-FES for trajectory C ($p < 0.01$) and there was no significant difference for trajectories A and B. Consecutive trials (trial 2 to 4 versus 8 to 10) were analysed to identify if accuracy improved with repetition. In the active tasks, repetition improved accuracy for the FF-V controller with all trajectories (A: $p < 0.002$, B: $p < 0.008$, C: $p < 0.002$), for the FB-V controller with trajectories A ($p < 0.02$) and B ($p < 0.004$), and for No-FES with trajectory C ($p < 0.002$). For the passive tasks, repetition did not create statistical differences.

Questionnaires

The questionnaires indicated that the perceived muscle fatigue increased throughout the study ($p < 0.004$), frustration was higher with FES than without FES ($p < 0.05$) and comfort and other NASA-TLX components did not change significantly throughout the study.

Discussion

The goodness of fit of the force to pulse width model was better with the Hammerstein model than with the piecewise linear or transfer function models. The goodness of fit was within literature cited values [12], [14], yet large modelling errors led to large force tracking errors in the passive tasks when feedforward-only control was used. The feedback from a grip force sensor improved the force tracking results significantly in both the passive tasks and complex active tasks. The accuracy and time delay errors observed could be improved with higher frequency hardware and predictive and adaptive modelling and control algorithms based on force and electromyography. These results demonstrate the utility of closed loop FES-assistance in improving performance both as an assistive device when voluntary muscle activation is not essential and to level the playing field in rehabilitation tasks when voluntary muscle activation is desired.

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Influence of Vibration Stimuli Applied on the Quadriceps Femoris Muscle during Functional Electrical Stimulation Induced Cycling

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Abstract— *FES-cycling is an approach that is recommended in certain instances to improve muscle strength and mass, blood flow and power output. However, the control of FES-cycling in individuals with movement disorders such as spinal cord injury is challenging. The inherent muscle fatigue related to FES and involuntary muscle spastic activity following injury degrade cycling performance. Therefore, a hybrid rehabilitation strategy to adjust the muscle force-generating capacity is well-motivated to cope with muscle fatigue and spastic behavior. Emergent results have reported the use of vibratory stimuli to induce torque and muscle activity adaptations when applied on the muscle tendon or belly. However, the interaction between muscle vibration and FES during cycling is unknown. In this paper, vibration stimuli were applied on the quadriceps belly concurrently with FES during cycling at 60 RPM. An electric motor assisted to keep the target cadence while the rider received intermittent FES and vibration. Four able-bodied individuals were recruited for two FES-cycling trials with and without vibratory stimuli. The mean active torque, fatigue time and fatigue rate are reported for all participants.*

Index Terms- *FES-cycling, Vibration, Torque, Fatigue*

I. INTRODUCTION

Neurological disorders such as spinal cord injury (SCI) result in limited limb coordination, spasticity, and diminished muscle strength. Functional electrical stimulation (FES) has been used to facilitate lower-limb movement and improve muscle mass, muscle strength, bone mineral density, and blood flow [1-2]. However, muscular fatigue develops more rapidly using FES than volitional contractions, limiting the overall effectiveness of FES [3-4]. This phenomenon is due to the reverse recruitment order of motor units (i.e., opposite to the size principle) or recruitment of motor units using a nonselective, synchronous and spatially fixed pattern [5].

Robotic exoskeletons and motorized cycles are combined with FES to assist the user complete a task. An example of such a hybrid system is motorized FES-cycling, where surface electrical stimulation is applied to multiple muscle groups to evoke active torque complemented by the assistance of an electric motor [6]. FES-cycling is recommended for people with upper-limb pathologies and impaired sensory feedback who are excluded from gait training or other high cardiovascular exercises. Motorized assistance enables repetitive practice and aids to delay the onset of muscle fatigue. However, providing more machine assistance than

needed can induce passive cycling and reduce the therapeutic benefits of FES. Hence, motivation exists to electrically stimulate the lower-limb muscles for prolonged periods during cycling. However, inevitably muscle fatigue settles, thus inducing a decay in the peak force generated by the muscles. An additional challenge for FES-cycling in individuals with SCI is the physical interference associated with spasticity characterized by muscle spasms and co-contractions. Involuntary muscle spasms limit the duration, intensity and dosage of active cycling. Hence, despite the benefits of FES-cycling, muscle fatigue and physical disturbances resulting from spasms interfere with cycling and degrade the functional gains. There is a need to improve hybrid rehabilitation strategies to cope with these challenges and enable a wider adoption of FES-cycling at home and the community.

Mechanical vibration or vibratory stimuli have been implemented to provide sensory feedback in application to alleviate chronic pain [7], gain muscle power [8], induce muscular activity, improve lower limb kinematics, and enhance conventional resistance exercise gains [9-10]. Customized motor-vibration systems have been designed for grip force testing or upper arm rehabilitation [9] and whole-body vibration (WBV) platforms [10-11]. Moreover, hand-held vibration devices are used to manually apply the vibration over muscles. WBV and local vibration have reduced spasticity and increased muscle activity attributed to reflex activity modulation [12-13]. The vibration frequencies in [12-13] range from low frequencies 20-50 Hz for WBV to high frequencies 300-500 Hz using local vibration devices. Vibration has increased muscle activity, reduced sway while standing, and induced muscle forces when applied to the Achilles tendon [14]. The increase in muscle activity due to vibration has been explained through muscle spindle-induced reflexive recruitment of inactive motor units [11,15]. The modulation of afferent inputs achieved through tendon and muscle vibration is known to be a strong stimulus for the activation of muscle spindle primary endings, thereby stimulating sensory and motor cortical areas [15]. However, it is unknown whether vibratory stimuli applied during FES-cycling can influence the force generated by muscles and consequently with muscle fatigue or spastic muscle activity.

In a recent study, constant superimposition tendon vibration had no effects on wide-pulse low frequency neuromuscular electrical stimulation (NMES) applied on the quadriceps during plantar flexion motion [19]. It was suggested that NMES induced saturation of the Ia afferents and, thus, the muscle was over activated. It has been also suggested that vibration may be more effective if it is brief or intense to produce a synchronous afferent flow [20].

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Motivation exists to examine how to modulate the vibration timing and magnitude. The objective of the present study is to assess the impact of mechanical vibration in the muscle active torque output during electrically elicited contractions.

In this paper, the goal is to investigate the effects of vibratory stimuli applied to the quadriceps muscle belly during FES-cycling. A wearable garment with vibratory motors is placed on the surface of the quadriceps concurrently with a single-channel synchronous FES on both legs to examine the active torque produced. This paper examines the effects of vibration stimuli applied to the quadricep femoris during dynamic contractions using a similar device as the one developed in [21], which was tested for isometric contractions. Experiments were conducted on four able-bodied individuals to assess the feasibility of the hybrid cycling approach.

II. METHODS

A. Subjects

Four healthy subjects (aged 24.25 ± 5.25 years) participated in the study. Each participant gave written informed consent to enroll in the study, as approved by the institutional review board at Syracuse University. All the participants had prior experience with similar FES-cycling protocols but not with the application of vibratory stimulus.

B. Apparatus

The testing apparatus consists of a recumbent cycle (Sun Seeker ECO-TAD SX) mounted on an indoor trainer, adapted with orthotic boots, and equipped with a 24 VDC brushed electric motor. A torque transducer (SRM, Germany) was utilized to measure the cycle crank torque. An optical encoder (US Digital) was coupled to the cycle crank to measure the crank position. A data acquisition device (Quanser QPIDE, Quanser, Canada) was used with a personal computer executing MATLAB/Simulink 2018a (MathWorks Inc) for data logging with a sampling rate of 1 kHz. An analog motor driver (Advanced Motion Controls) commanded the current control to the electric motor.

Biphasic symmetric rectangular stimulation pulses were delivered by a current controlled electrical stimulator (RehaStim, Hasomed GmbH, Germany). A single stimulation channel was used with a pair of 3" by 5" bipolar self-adhesive surface electrodes placed over the distal-medial and proximal-lateral portions of the quadriceps muscle group on both legs [surface electrodes for the study were provided compliments of Axelgaard Manufacturing Co., Ltd. (ValuTrode®, USA)]. The mechanical stimulus was applied to the quadriceps muscle belly using vibratory motors of 9 mm diameter (Pico Vibe™, Precision Microdrives, United Kingdom) affixed to the leg using an adjustable garment. Each vibratory motor was controlled by applying a 3V voltage command to achieve a frequency of 230 Hz, which was perceptible, and a vibration amplitude of 7g (g-force or acceleration of gravity). Six vibration motors were used to apply the vibratory stimuli bilaterally. The garments were secured to the participant's thighs using Velcro straps to provide an appropriate fit and ensure direct contact between the vibration motors and the muscle belly. The placement of the garment with the vibration motors and FES electrodes is depicted in Fig. 1.

C. FES and Vibration Protocols

A pretrial cycling test was conducted on a separate day and prior to the main cycling trials to determine the pulse width

for each participant (and to prevent influencing the results of the subsequent cycling trials). The pretrial test was performed at 60 revolutions per minute (RPM) with motorized assistance. The pulse width was selected as the minimum to evoke an active torque output of 4 N·m. This torque threshold was selected to prevent fast muscle fatigue buildup during the durations of the cycling trials. The selected pulse width for each participant was used during the cycling trials described below. For all cycling trials, the stimulation frequency and current amplitude of FES were fixed at 60 Hz and 80 mA, respectively, as done in other FES-cycling results [6].

At the beginning of each cycling trial, a passive torque test was performed where the electric motor passively rotated the rider's legs [6] at a constant cadence of 60 RPM without FES to obtain an estimate of the rider's passive torque. Thus, the active torque generated by the muscles was determined by subtracting the passive torque estimate from the real-time torque measurements. The FES-cycling trials with and without vibratory stimuli were conducted for 2 minutes with the electric motor tracking the target cadence using a robust sliding-mode controller. FES-cycling testing included two trials; one trial without vibration (i.e., typical FES-cycling) and another trial with vibration applied on the quadriceps bilaterally. Participants were instructed to avoid providing voluntary contribution during both cycling trials. FES-cycling was assisted by the electric motor to maintain a cadence of 60 RPM. Each cycling trial started with the electric motor passively bringing the rider to the target cadence for 25 seconds before applying FES and vibration (for the vibration trial). After reaching the desired cadence, FES was applied in open-loop fashion during all cycling trials only within kinematic efficient regions of the crank cycle for each participant [6]. Across all subjects, FES was applied within the interval of [66, 157] degrees. Vibration was applied concurrently with FES only. A period of 24-72 hours was enforced between the sessions for muscle recovery.

D. Data Analysis

For all trials, data collection started at the point at which the motor brought the rider to the target cadence. The active torque was computed and stored only during the crank angles where FES was applied (i.e., FES regions). A contraction is the average of the active torque of FES regions happening twice every cycle. The mean active torque for every contraction was averaged with a moving window of 1-second; it was then normalized by the maximum active torque produced during the trial for each participant. The normalized curves for all participants were combined and averaged. Three metrics to assess performance were compared across trials: mean active torque, fatigue time, and fatigue rate.

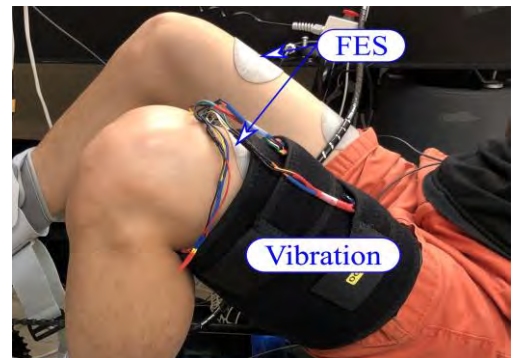


Figure 1. Participants seated in the cycle wearing a garment on both thighs (not depicted here for clarity), which contains the vibration motors. The pair

of FES electrodes lie below the garment and are placed in the proximal and distal part of the quadriceps muscle group on both legs.

Fatigue time is the elapsed time between the maximum torque contraction and the contraction at which the torque decreased by 30% of the first contraction (measured in the number of contractions) [21]. Fatigue rate is the slope of the best fit linear curve of the function of torque output over 120 contractions. Fig. 2 depicts the normalized mean torque of all participants over the contractions displaying each activation of FES.

III. RESULTS

The normalized active torque is shown in Fig. 2 as a function of contractions for the four participants during both cycling trials. Mean active torque, fatigue rate and fatigue times are presented for each participant (including the used pulse width) in Table I for the FES-cycling trials with and

without vibration along with the first and third quartile (Q1 and Q3), respectively.

TABLE I. Mean active torque, fatigue time and fatigue rate for the FES-cycling trials with and without vibration across the four subjects. The pulse width used for each subject was kept constant for both cycling trials.

Subject-Pulse Width	Mean Active Torque		Fatigue Time		Fatigue Rate	
	NO VIB	VIB	NO VIB	VIB	NO VIB	VIB
S1-75	0.4887	0.5695	42	55	-0.0094	-0.0094
S2-80	0.4461	0.3864	41	41	-0.0095	-0.0113
S3-80	0.5254	0.5005	28	33	-0.0058	-0.0072
S4-90	0.5663	0.5321	35	33	-0.0072	-0.0063
Q1	0.3878	0.4791	29.5	31.5	-0.0094	-0.0094
Median	0.4416	0.5117	43	37	-0.0088	-0.0070
Q3	0.5598	0.5499	52.5	52.5	-0.0073	-0.0062

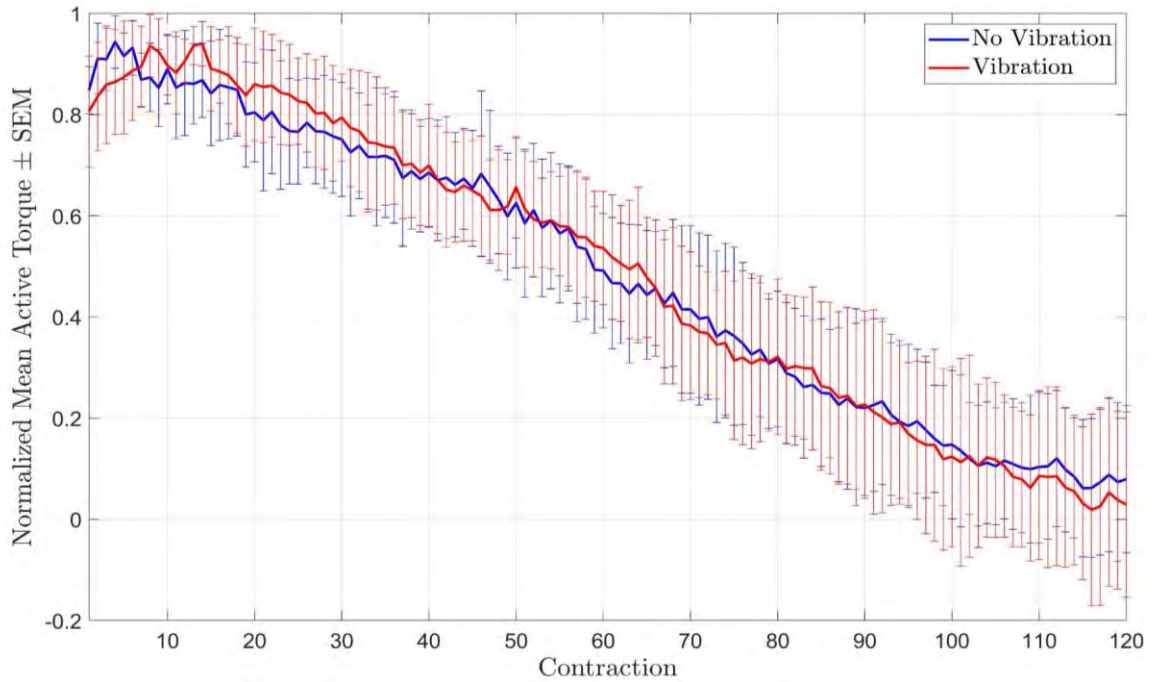


Figure 2. Each data point represents the mean value of the active torque over all participants. The maximum torque for each participant was achieved at a different number of contractions. SEM stands for the standard error of the mean.

IV. DISCUSSION

Vibration stimuli applied to the tendon or muscle belly has been suggested to induce motor activation and modulate afferent inputs [17, 20]. Moreover, vibration targeting tendons has shown to attenuate spastic-like activity, which may aid to mitigate involuntary muscle spasms in people with SCI [22]. Vibration applied to the muscle belly of the quadriceps, hamstrings, and tensor fascia latae muscles has elicited step-like responses in individuals with SCI [22]. Prolonged vibrational stimuli over the rectus femoris for 10 minutes shows significant reduction in leg spasticity after SCI [23].

The motivation of the present work was to examine the influence of vibration during FES-cycling. The electric motor achieved satisfactory cadence tracking because there was a difference of 1.76% ($p=0.44$) of standard deviation of cadence between cycling with (0.172) and without (0.169) vibration for all trials. Hence, cadence was consistent during all cycling trials. There were no statistically significant differences of mean active torque between the cycling trials with and without

vibration. The study only tested 4 healthy young subjects (e.g., data set was limited) and a rest period of 24-72 h was used to prevent muscle fatigue to influence the cycling trials. Hence, a potential different trend can be obtained with the recruitment of individuals with SCI and randomizing the order of the trials.

Fatigue rates were linearized for best fit ($R^2=0.98$). The mean fatigue rate for all participants was 5.23% greater for the trial with vibration than the trial without vibration. However, fatigue rates highly varied across participants. The trial with vibration yielded 10.75% lower standard deviation of the active torque than the trial without vibration. This can be interpreted as vibration reducing the variance of active torque output compared to the no vibration trial. Along with the motivation of the present study to examine the influence of vibratory stimuli for adapting the muscle capacity to evoke active torque, previous studies have shown isometric torque increments during electrical stimulation coupled with vibratory stimuli. In [24], increased extra torques (generated by vibratory stimuli) were found to reach values up to 50% of the maximum voluntary contractions on top of the peripheral

torque elicited by percutaneous electrical stimulation. Vibratory stimuli of 100 Hz for 2-second periods were applied to the Achilles tendon while alternating with electrical stimulation. However, some subjects exhibited no extra force produced by vibration.

The combination of the vibratory and electrical stimuli may provide neural adaptations and enhanced muscle performance, optimized by stimulation of sensory axons. Even though the present work also investigated the coupled scenario of vibration and electrical stimulation, there are differences compared to the study in [24]. First, in [24] the Achilles tendon was vibrated rather than the quadriceps muscle belly, which may cause a modified effect in the afferent input. The FES fatigue bouts, beyond using different frequencies, differed significantly in the stimulation duration, with a much longer duration for the present work. Experiments computed torque under isometric conditions while current experiments were performed pedaling on a bicycle. Finally, in [24] the authors may have been able to trigger a centrally mediated excitatory mechanism (in addition to the peripheral sensory activation) by applying vibration to the Achilles tendon; however, there is no evidence of such a mechanism in the present work.

The effectiveness of vibration stimuli may vary according to several neuromuscular factors. In this cycling paper, the vibratory stimulus was applied on the skin superficial to the quadriceps muscle belly at a low amplitude and relatively high frequency. Vibration motors are placed on the surface of the skin as compared to tendon vibration where the mechanical device physically taps against the tendon with a fixed magnitude. Stimuli with a frequency of 100 Hz have been shown to suppress muscle sensation [24]. Although this sensation suppression was not rigorously assessed during the cycling trials, several participants experienced a similar muscular output torque suppression sensation when vibration was applied concurrently with FES. Thus, after reaching a frequency threshold, vibration force suppression plateau. Therefore, motivation exists in future work to examine the influence of different vibration frequencies in FES-cycling.

Further evidence of torque facilitation or depression (i.e., increased or reduced torque) due to the effect of the vibratory stimuli during FES-cycling is to be obtained with a larger sample size. The effects of vibration on muscle fatigue and spasticity in individuals with SCI also remains to be investigated. Future work will also include modeling and analysis of the fatigue rates during cycling as in [25]. Exploring vibration to ease painful sensation for FES applications is also to be explored. The optimization of vibration and electrical stimulation parameters will be explored for different cycling cadences.

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ROBOT-ASSISTED TRAINING WITH FUNCTIONAL ELECTRICAL STIMULATION ENHANCES LOWER EXTREMITY FUNCTION AFTER SPINAL CORD INJURY

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Abstract:

Introduction: Functional Electrostimulation (FES) synchronized with robot-assisted lower extremity training is used in spinal cord injury (SCI) to promote residual function.

Methods: Data of SCI inpatients who trained lower limb mobilization on a stationary robotic system were retrospectively analyzed. The primary outcome was the improvement muscle strength (N) from the first through to the last training, during FES-induced as well as voluntarily induced flexion (F) and extension (E). The secondary outcome was the sum score of voluntary muscle function in the lower limbs before and after the training period.

Results:

Data from 72 patients with SCI (AIS A-D) were analyzed. FES-assisted strength increased ($p < 0.001$) from 25.2 to 44.0 N, voluntary force ($p < 0.001$) from 24.4 to 39.9 N in E. FES-assisted F ($p < 0.006$) increased from 14.1 to 19.0 N, voluntary F ($p < 0.005$) from 12.6 to 17.1 N. There was a significant correlation between the increase in FES-assisted force and voluntary F ($r = 0.730$, $p = 0.001$) as well as between the increase in FES-assisted force and voluntary E ($r = 0.881$, $p < 0.001$). The sum score in muscle test increased from 15 to 24 points.

Conclusion: Robot-assisted training with FES seems to support the regeneration of residual functions after SCI. This is evidenced by an improvement in motor function and strength in the lower limbs.

Keywords: Functional electrical stimulation, Spinal Cord Injury, Robotic, Neuromodulation, Lower limb function

Introduction

Restorative neurology works through the modification of residual nervous system function and is part of the rehabilitation in spinal cord injuries (SCI). Techniques of neuromodulation belong to restorative neurology¹. One of those techniques is functional electrical stimulation (FES), applied with surface electrodes to the treated muscle or muscle group. Depending on the type of lesion, i.e. whether the upper motor neuron or lower motor neuron is damaged, the stimulation occurs via the nerve or directly through the muscle. The approach via nerve needs intact peripheral nerves and neural signal processing of the section of spinal cord which remains after the impairment². The following article will focus on patients with an upper motor neuron lesion due to a SCI. FES is often applied in the acute and sub-acute stages after SCI to support the neurological

recovery and provide neuromodulation^{3,4}. Due to neuromodulation, motor function and muscle force often increase. Synchronization of FES with robotic-assisted training (RT) is an approach to promote neurological recovery.

The aim of the retrospective data analysis was to investigate the difference between FES-induced and voluntarily induced strength (Newton (N)) of the lower limbs in patients with SCI in the sub-acute phase using a stationary robotic device (MotionMaker™).

Methods

Data of inpatients with acute and sub-acute SCI in their primary rehabilitation were included in this retrospective analysis. They actively trained limb mobilization for neuromodulation using a stationary robotic system (MotionMaker™). The MotionMaker™ is a stationary robotic device that performs movements of the lower limbs in extension and flexion. A closed loop electrical stimulation system allows the application of stimulation in real time based on integrated sensors inside the orthoses, that enable the assessment of position and force during the movement. Each training session consisted of FES-induced and voluntary repetitive movements of the lower limbs in flexion and extension. First the voluntary movements were performed followed by the FES-induced movements. No electrical stimulation was applied during the voluntary movements of the legs. The integrated power sensors measure the voluntary force of the extensor and flexor muscles of the right and left leg separately. In contrast during the FES-induced extension and flexion of the lower limbs, the following muscles were bilaterally stimulated: M. gluteus maximus, M. quadriceps (rectus femoris, vastus medialis and lateralis with separate electrodes each part), Mm. ischiocrurales, M. gastrocnemius, M. tibialis anterior (Figure 1). By performing the FES-supported movements the force was measured through power sensors located in the footrests of the device. To perform extension of the legs the M. gluteus maximus, M. quadriceps (rectus femoris, vastus medialis and lateralis) and M. gastrocnemius were stimulated. Whereas, the Mm. ischiocrurales and the M. tibialis received stimulation to perform the flexion. Stimulation parameters remained unchanged for each patient. The pulse duration was 300 µsec and the frequency 35 Hz. The amplitude was individually determined for each patient but remained unchanged over the training period.

Primary outcome was the improvement in strength (N) of the legs from the first through to the last training session during FES-induced as well as voluntary induced flexion and extension. Secondary outcome was the sum score of active muscle function of the seven lower limb muscles having been stimulated ⁵. The muscle test was performed twice, before and after the training period. Group correlation was analyzed using the Spearman's correlation

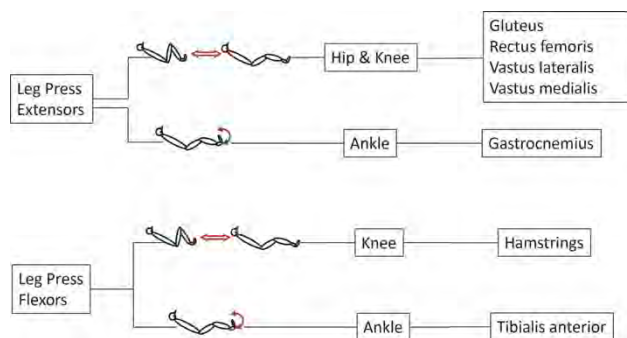


Figure 1: Movements of the lower limbs and stimulated muscles during extension and flexion performed on a stationary robotic system. The movement is named in the first box, followed by the illustration of the movement and the corresponding joint. The stimulated muscles are listed in the last box.

Results

72 patients with SCI (AIS A-D, mean age and time since lesion 49.94 and 246.6, respectively) conducted a mean of 12 training sessions.

FES-assisted strength increased ($p<0.001$) from 25.2 to 44.0 N and voluntary strength ($p<0.001$) from 24.4 to 39.9 N. The strength increased in FES-assisted F ($p<0.006$) from 14.1 to 19.0 N and in voluntary F ($p<0.005$) from 12.6 to 17.1 N (Figure 2). There was a significant correlation in increase of strength between the FES-assisted and voluntary F ($r=0.730$, $p=0.001$) and E ($r=0.881$, $p<0.001$) (Table 1). The sum score

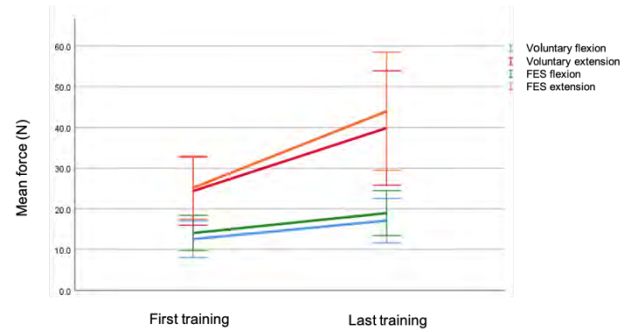


Figure 2: Development of the strenght in Newton presented as Mean and 95% Confidence Interval (CI) using FES-induced and voluntary movements at the first and last training session on the MotionMaker™ (n=72)

Table 1: Correlation of FES-induced strength and voluntary muscle force for leg extension and flexion

Correlation of the increase in force between FES-induced force and voluntary muscle force		
Extension	$r=0.881$	$p<0.001$
Flexion	$r=0.730$	$p<0.001$

Discussion

The result of this retrospective study demonstrates the increase in FES-induced as well as in voluntary strength of the lower limbs in patients with complete and incomplete SCI. The fact that FES can increase torque and power output in persons with motor complete and incomplete SCI has been described in several previous studies ⁶⁻⁹. Our results are therefore consistent with the existing literature. Nevertheless, our results highlight some additional interesting observations. The technical features of the MotionMaker™ allowed us to differentiate between the increase of the FES-induced force of the extensor muscle group and the flexor muscle group of the legs. The extensor muscle group gained more strength than the flexor muscle group. The FES-induced extension increased by 18.8 N in contrast to the FES-induced flexion that only increased 4.9 N. Similar findings were detected regarding the voluntarily induced strength that increased by 15.5 N for extension and only by 4.4 N for flexion. One explanation for this discrepancy could be the difference in the number of stimulated muscles. The stimulation in extension included three muscles, whereas the M. quadriceps having three separate pairs of electrodes for each muscle part (rectus femoris, vastus medialis and lateralis). In contrast, the stimulated flexor muscle groups only comprise two muscles, namely the hamstrings and the dorsiflexor of the foot. It should also be taken into account that based on clinical observation, mostly the flexor muscles, namely the hamstrings, show slower and less neurological recovery than the extensor muscles during primary rehabilitation. Nevertheless, both the correlation between FES-induced and voluntarily induced movements for extension and flexion were significant.

This result might endorse our above-mentioned suggestion. In other words, the patients were probably not able to use and transfer the gain of the FES-induced force into their voluntary leg movements in flexion as good as in extension. That leads to another clinical observation that patients, training with FES on the MotionMaker™ reported difficulties in coordinating their own voluntary muscle activity with the FES given activity of the stimulated muscles, especially during flexion movements. However, it must be considered that the reproducibility of force may be reduced due to day-to-day variation of the electrode placement.

Looking at these promising results the question of transferring the applied method from the lower limbs to the upper limbs arises. There is some evidence, that rhythmic and alternating locomotor output, such as leg or arm cycling is mediated by a spinal central pattern generator (CPG)¹⁰. In addition, a supra-spinal input to the spinal cord is necessary¹¹. Forman et al could illustrate that the corticospinal excitability of the M. biceps brachii increased in dependence of the cadence by arm cycling¹². This increase is relevant because of the importance of the corticospinal pathway as a descending motor pathway involved in the voluntary control of motor output. One could suggest that by combining arm cycling with FES, the effect could be intensified. Bisio et al demonstrated that motor training in combination with action observation and peripheral nerve stimulation could increase the excitability of motor cortical areas, mainly the primary motor cortex¹³. Based on clinical observation FES supported arm cycling in the acute and subacute phase after SCI might enhance motor learning and thus motor recovery. Systematic clinical trials are required.

Conclusion

Robot-assisted training with FES seems to have an influence in terms of neuromodulation on residual function. This can be used to support neurological recovery. The result is expressed in an improvement of motor functions and an increase in strength of the lower limbs.

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EFFECTS ON POWER OUTPUT AND MUSCLE OXYGENATION OF TWO ELECTRICAL STIMULATION-INDUCED CYCLING MODALITIES

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Abstract:

Functional electrical stimulation (FES)-induced cycling can be utilized as preventive exercise training to improve health and reduce cardiovascular risk factors. Previous training studies have yielded inconsistent effectiveness. Especially the exercise dose, the training modality and the optimal moment for exercise initiation remain ambiguous. This study highlighted the differential effects of high intensity interval training (HIIT) versus moderate continuous training (MCT) FES-cycling that were deployed in two patients with spinal cord injury (SCI). One participant with sub-acute and one with chronic SCI completed 23 FES-cycling sessions three to four times per week with a duration of 42 minutes per session. Changes in power output (PO) and muscle metabolism were assessed at pre- and post-training periods. Furthermore, changes of leg circumference were assessed. Our findings revealed an increase in PO from study start to end in both participants, as well as an increase in the rate of oxygen consumption of m. rectus femoris.

Keywords: Spinal Cord Injury, Cardiovascular Fitness, FES-induced cycling, NIRS, Power Output

Introduction

SCI has an impact on body composition, regardless of whether the injury is caused by traumatic or non-traumatic aetiology. As a consequence of SCI, there is a decline in skeletal muscle mass, accompanied by a relative increase in adipose tissue¹. The reduction of skeletal muscle tissue commences approximately one month after the injury with the loss of the slow oxidative type I muscle fibres, and an increase in type II fibres. This “fibre type shift”, with a predominant expression of fast glycolytic type II muscle fibres, commences after the first month and muscle tissue reorganization may be on-going for up to two years post-injury^{2,3}.

With the transformation of muscle tissue composition also come adaptations around and within the skeletal muscle cells. The decline in capillary-to-fibre ratio reflects the reduced need for oxygen within the muscles, since oxidative activity is lower in the ‘paralyzed’ skeletal muscles⁴. The changes within the muscle cell are a decline in the density, as well as the function, of mitochondria⁵. McCully et al. have reported a decrease of roughly 50% in mitochondrial function in people with chronic SCI by

assessing phosphocreatine resynthesis rates after exercise by P-magnetic resonance spectroscopy⁶.

Furthermore, FES-induced cycling has been shown to increase PO in people with chronic SCI^{7,8,9}. A recent review has encouraged the application of FES-induced leg cycling for 30 minutes around thrice a week to achieve optimal results regarding muscle health, PO and aerobic fitness¹⁰. Warburton et al. additionally emphasizes the importance of cardiovascular exercise in this population as a way to prevent cardiovascular disease¹¹.

The current pilot study sought to compare two FES-cycling exercise modalities in terms of the physiological adaptations to 6-8 weeks of training. High-intensity Interval Training (HIIT) and Moderate Continuous Training (MCT) were deployed in 2 case studies.

Methods

One 29-year-old male with subacute paraplegia (T6, ASIA A) performed HIIT and the other participant was a 27-year-old man with chronic tetraplegia (C7, ASIA A) who underwent MCT. Both were novice to FES, and they completed 23 sessions of FES-induced leg cycling training (Rehamove2, Hasomed GmbH) three to four times per week with an average duration of 42 minutes per session. HIIT comprised two-minute intervals at 120mA interspersed with 2-minute non-stimulation recovery periods. MCT was 42-min continuous exercise, keeping the stimulation intensity constant at 90mA. The remaining parameters of FES were identical for training: 50Hz, 250µs, a pedal resistance of 20kg and 50 rev·min⁻¹ without ramping. The current was a symmetrical biphasic rectangular waveform. Self-adhesive Axelgaard PALS electrodes were placed on to the m. quadriceps, m. biceps femoris (5cm x 9cm) and mm. glutei (7.5cm x 13cm) bilaterally. The cycling ergometer derived the PO every second. Before and after the training period (six to eight weeks), a 12-minute incremental intensity test at a frequency of 35Hz and a pulse duration of 250µs was conducted, where the current amplitude was increased by 10 mA every two minutes from 80mA until 130mA (Fig. 1).

Muscle oxygen saturation was monitored using near-infrared spectroscopy (NIRS; Portamon, Artinis Medical Systems) with a sampling rate of 10Hz and placing the sensor on the m. rectus femoris of the right leg. Muscle oxygen consumption (mVO₂), reoxygenation rate (Δreoxy) and recovery half-time (t_{1/2}) were performed after the

incremental exercise test by applying super-systolic arterial occlusion to the right upper thigh for ~8 minutes. NIRS data were analysed by Oxysoft software after filtering the data with a 5s Gaussian moving average. Before applying the NIRS sensors, adipose thickness was assessed via ultrasound to assure that the light would

penetrate the muscle appropriately. The leg circumference at the mid-thigh was measured according to the method described by Heesterbeek et al. before and after the training period¹². These pilot data are first patients recruited into a randomized clinical trial (NCT03621254).

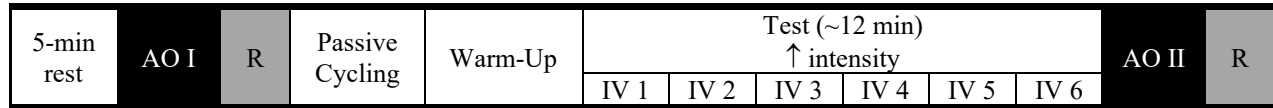


Figure 1: Incremental test protocol

AO I/II: first/second arterial occlusion; R: rest; IV 1 - IV 6: interval 1-6

Arterial occlusions were conducted before and after the incremental test. The intensity of FES was increased every two minutes from 80mA up to 130mA.

Results

The exercise test and thigh circumference results are displayed in Table 1 below.

PO over the last ten training sessions plateaued around 6.8 ± 0.8 W for the MCT while this was 30.4 ± 1.1 W for the HIIT (Fig. 2). Further analysis of the incremental exercise test data revealed a peak PO of 11.3W for the participant with tetraplegia doing the MCT while 20.9W was attained by the participant with paraplegia doing the HIIT.

The mVO_2 , derived from NIRS, increased in both participants with the increase being relatively higher after MCT (81%) compared to HIIT (50%). The Δ reox and $t_{1/2}$ remained unchanged after training for the MCT. In contrast, the time for reoxygenation was decreased after HIIT by 50%.

The leg circumference was increased by 5 cm following HIIT, while it increased to a lesser degree (3.5 cm) after MCT at mid-thigh landmark. Tissue thickness remained constant throughout training.

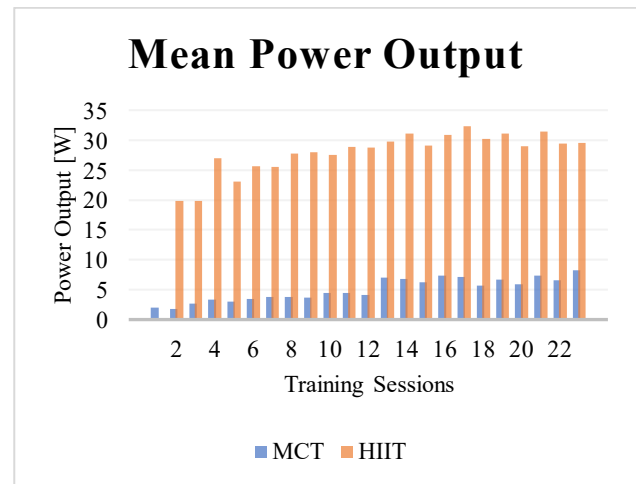


Figure 2: Mean PO - Training

Table 1: Results

	HIIT			MCT		
	Pre	Post	Δ (%)	Pre	Post	Δ (%)
mVO_2 [mL/min/100g]	0.11	0.22	0.11 (50%)	0.03	0.16	0.13 (81%)
Δ reox [μM/s]	3.52	3.99	0.46 (12%)	4.05	3.71	-0.35 (-9%)
$t_{1/2}$ [s]	38.75	19.85	-18.90 (-50%)	16.95	18.20	1.25 (7%)
PO [W]	0.0	20.9	20.9 (100%)	4.6	11.3	6.7 (58.9%)
Thigh circ. [cm]	44.5	49.7	5.2 (10%)	45.0	48.5	3.5 (7%)

mVO_2 : oxidative capacity of m. rectus femoris; Δ reox: reoxygenation rate; $t_{1/2}$: recovery half-time; PO: power output; HIIT: high intensity interval training; MCT: moderate continuous training; diff: difference

Discussion

The gain in PO was accompanied by an increase in the local muscle capacity to utilize oxygen after training.

In the HIIT, the PO during training at 50Hz was 26.8W and hence superior to the PO of 20.9W at the lower frequency of the incremental test. The mean PO reached by the participant with tetraplegia were inverse to the results of the previous: stimulation at 35Hz yielded 11.3W and training at 50Hz yielded only 5.0W. The reason for this might be the fact that the fibre shift was already more advanced so that only a very small number of type I oxidative fibres were present. As a consequence, the stimulated muscles probably fatigued a lot faster in the 40-

min training session and the PO decreased over time. No additional motor units could be recruited at 50Hz compared to 35Hz. These values of mean PO during testing are comparable to those reported by Eser et al. when at a stimulation frequency of 30Hz⁷.

The participant with subacute SCI started off with a PO of 0W, which compares to Janssen et al.⁸, and it increased up to 20.9 W at the last session. The mean PO was roughly doubled in the participant completing the MCT, which is similar to findings of Thrasher et al.⁹.

From the metabolic data in Table 1, it is apparent that there was a trend towards a more efficient oxygen utilization following FES-cycle training, especially with the HIIT

protocol. Although the change in mVO_2 in the person with tetraplegia (+81%) surpassed that of the person with paraplegia (+50%), the findings with muscle reoxygenation did not change in the former case. In contrast, the HIIT protocol led to a better oxygen utilization, an improved reoxygenation time constant (-50%) and more efficient reoxidation rate (+12%) following arterial occlusion. This might be due to the participant being in the subacute phase of post-SCI recovery who started training only 60 days after his accident and perhaps retained a higher percentage of oxidative fibres with greater mitochondria preservation.

Regarding the relatively large gain in leg circumference, this most likely presents a gain in muscle mass as the adipose tissue thickness remained similar throughout the study period. Our finding is supportive of previously described outcomes regarding the increase in PO, and is in accord with a recent review¹⁰.

If we could transfer those results to the gluteal musculature, both training protocols would constitute a potent preventive measure for skin injuries in people with SCI, which would confirm the conclusions by Baldi et al.¹³.

Finally, both protocols are safe to apply in patients with SCI. No adverse events were reported during study participation. Moreover, these results show that NIRS is applicable in patients with SCI as long as it is assured that the skin and adipose tissue thickness stays well below the 17.5mm penetration depth of the near-infrared light. Both protocols led to promising results regarding PO and metabolic data. However, the data of only two participants cannot be used to make general assumptions about the superiority of one protocol over the other. Since these findings are preliminary ones from an ongoing randomized clinical trial, further results will grant insight into optimal training design and parameters with regards to FES-cycling exercise to augment cardiovascular health and reduce disease risk.

In future studies, special attention should be directed to clustering participants according to their diagnosis (tetraplegia vs. paraplegia) as well as to the time after injury in the statistical analyses. The large increase in PO in the subacute participant is promising and presents an encouraging sign to start vigorous exercise training early after injury and prior to any significant muscle tissue reorganization.

Conclusion

Our work has shown that PO increased in both participants with different diagnoses following two different training protocols. Both training protocols revealed promising findings regarding cardiovascular training using FES-cycling and should be analysed using larger data sets and further stratification.

Acknowledgement

We would like to thank Kathrin Dopke, our study coordinator and the staff of the Sports Medicine department.

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LONGER DURATION CORTICAL AND PERIPHERAL STIMULATION MAY ENHANCE CORTICOSPINAL FACILITATION

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Abstract: The purpose of this preliminary study was to examine whether increasing the duration of simultaneous cortical facilitation and peripheral afferent recruitment increases corticospinal excitability. Intermittent theta burst (iTBS) was used to induce cortical facilitation, while functional electrical stimulation (FES) was used to activate the upper-limb muscles. A total of three interventions were tested in the preliminary study: cortical facilitation consisting of 600 pulses with FES applied simultaneously (iTBS600-FES; n=6), cortical facilitation consisting of 1200 pulses with FES applied simultaneously (iTBS1200-FES; n=2) and cortical facilitation consisting of 1800 pulses with FES applied simultaneously (iTBS1800-FES; n=1). Single-pulse transcranial magnetic stimulation motor evoked potentials (MEPs) were compared between before and after each intervention for 30 min. Results showed that MEP excitability increased immediately after iTBS600-FES intervention, but it returned to baseline 10 min after the intervention. There was no MEP change in iTBS1200-FES intervention, but a further facilitation in iTBS1800-FES intervention was shown. Overall, these findings suggest that increasing the number of iTBS-FES stimulation blocks (i.e., duration) may facilitate dose-dependent corticospinal modulation effects.

Keywords: Functional electrical stimulation; Theta burst stimulation; Simultaneous activation

Introduction

In recent years there has been a growing interest in non-invasive stimulation techniques that can promote changes in the excitability of human cerebral cortex, i.e., neuroplasticity. These techniques include patterned electrical stimulation of muscles and peripheral nerves, which is known as functional electrical stimulation (FES) [1]. Moreover, non-invasive brain stimulation via transient magnetic fields such as transcranial magnetic stimulation (TMS) and repetitive TMS (rTMS), has also been proven efficacious both clinically and in basic studies [2, 3]. Using neuromodulation, plastic changes can be induced in the central nervous system through temporal synchronization of cortical commands and afferent sensory feedback from the muscle [4]. However, longer duration of paired stimulations using FES and rTMS remain unclear.

In the current study, we addressed the question of whether repeated rTMS and FES applications in humans exert greater effects on the corticospinal excitability. Intermittent theta burst stimulation (iTBS), which is a proven and effective rTMS protocol was used to elicit long term potentiation (LTP)-like effects in the current study. A

block of iTBS consisted of three pulses delivered at a frequency of 50 Hz (per burst) applied every 200 ms for 2 s (10 bursts) and repeated every 10 s for a total 600 pulses (iTBS600). Up to three blocks of iTBS 600 pulses were applied together with FES simultaneously. We hypothesized that longer duration iTBS-FES interventions (i.e., increased duration) would increase corticospinal excitability in a dose-dependent manner.

Methods

Participants

A total of six participants (age: 20-33 years) with no history of neurological or psychiatric disorders participated in this study with different sample size in various preliminary interventions (for details, see below). All participants provided written informed consent in accordance with the principles of the Declaration of Helsinki.

Experimental protocol

Duration of simultaneous activation of cortical (iTBS) on primary motor cortex and peripheral (FES) stimulations on extensor carpi radialis (ECR) muscle were examined. Three different interventions were investigated, including: (1) iTBS600-FES (n = 6), iTBS600 was conducted simultaneously with FES during 200 s, with 2 s ON (stimuli on) and 8 s OFF (stimuli off, Fig. 1 and 2) [3]; (2) iTBS1200-FES (n = 2), iTBS1200 was conducted simultaneously with FES during 400 s, with 2 s ON and 8 s OFF (Fig. 2); (3) iTBS1800-FES (n = 1), iTBS1800 was conducted simultaneously with FES during 600 s, with 2 s ON and 8 s OFF

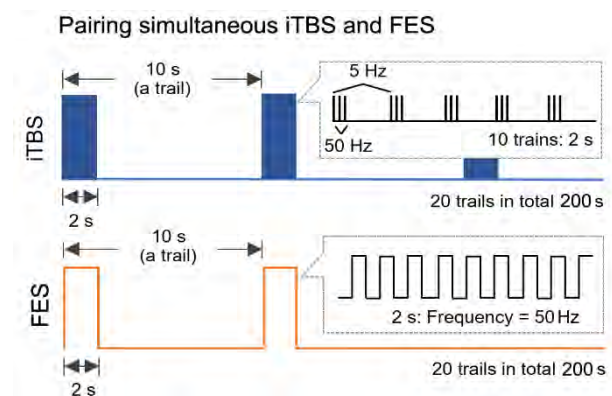


Figure 1: Flowchart of the synchronous activation of iTBS and FES.

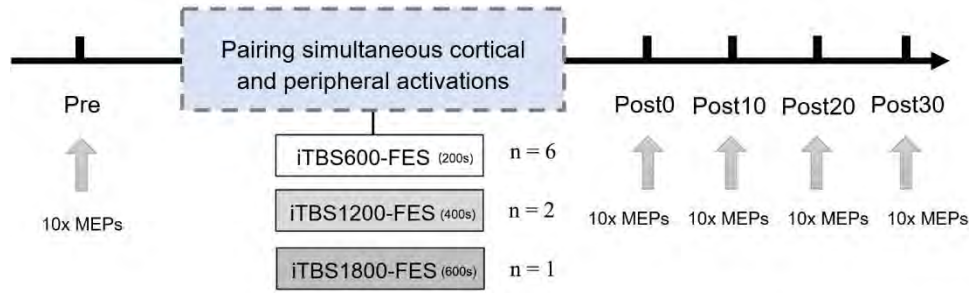


Figure 2: Experimental protocol.

(Fig. 2). FES in all interventions was applied at a frequency of 50 Hz (see Fig. 1). The cathode electrode was placed on ECR muscle belly, while the anode electrode was placed medially on the musculotendinous junction distal to the ECR muscle. The FES stimulation intensity was finally set to 150% of the identified motor threshold for each participant [5], resulting in average stimulation of 18.9 ± 1.7 mA.

Assessments were carried out to evaluate corticospinal excitability in ECR muscle through single-pulse TMS by eliciting motor evoked potentials (MEPs). Specifically, assessments were performed: before the intervention (Pre), as well as immediately (Post0), 10 min (Post10), 20 min (Post20), and 30 min (Post30) after combination protocol, as shown in Fig. 2.

Peak-to-peak MEP amplitude were measured for each trial for each participant. Ten MEP responses at each measurement point were elicited and averaged. All calculations were performed using a custom written script in MATLAB (2019a, The Math-Works Inc., Massachusetts, USA). A one-way repeated-measure analysis of variance (ANOVA) with a within-subject factor of time (Pre, Post0, Post10, Post20, Post30) was used to compare differences between MEP responses in each intervention. Data were deemed statistically significant if $p < 0.05$. All statistical comparisons were performed using SPSS (v. 22, IBM Corp., Armonk, NY, USA).

Results

Effects of longer duration pairing stimulations on ECR excitability

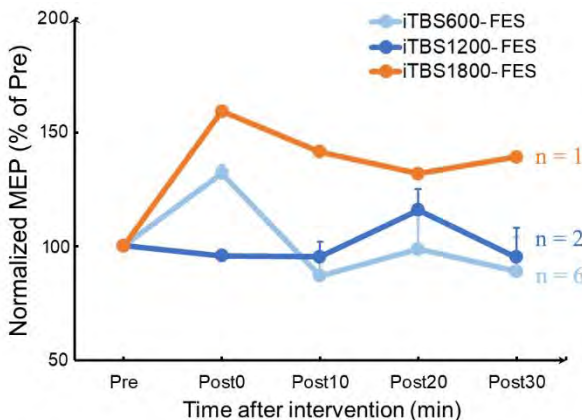


Figure 3: Effects of longer duration pairing stimulations on normalized MEP amplitudes. Values are reported as mean \pm standard error of the mean (SEM).

Fig. 3 shows the effect of longer duration of pairing cortical and peripheral stimulations protocols on the normalized ECR MEPs. Since the sample size is too small for two-way ANOVA, one-way repeated-measure ANOVA was conducted to compare the time effect in each intervention. For iTBS600-FES, one-way repeated-measure ANOVA showed that there was no significant effect of time factor ($F_{(4, 20)} = 1.613$, $p = 0.210$, $\eta_p^2 = 0.244$). For iTBS1200-FES, one-way repeated-measure ANOVA showed that there was no significant effect of time factor ($F_{(4, 4)} = 0.817$, $p = 0.532$, $\eta_p^2 = 0.449$). Although the statistic is limited by the preliminary study sample size, the results showed the trend that MEP excitability increased immediately after iTBS600-FES intervention but it returned to baseline after intervention. There was no MEP change in iTBS1200-FES intervention even at the Post0 measurement, but a larger facilitation in iTBS1800-FES intervention was observed from Post0 to Post30 (Fig. 3).

Discussion

In this preliminary study, we investigated whether increasing number of pairing simultaneous cortical facilitation and peripheral afferent recruitment increases corticospinal excitability. Our results showed that MEP excitability increased after iTBS600-FES intervention but it returned to baseline 10 min after the intervention. When it comes to iTBS1200-FES, no MEP change even in Post0. MEP increased from Post0 to Post30 in iTBS1800-FES intervention. It suggests that increasing the number of iTBS-FES stimulation blocks results in greater effects and were not grown linearly.

Previous reports have shown that iTBS1800 pulses alone over M1 resulted in a significant increase of cortical excitability (as reflected by MEP amplitudes) but not iTBS1200 pulses [6]. Our preliminary results have shown consistent results. Homeostatic metaplasticity could be used to explain the results. In other words, increased levels of synaptic activity (i.e., LTP-like effect) after stimulation are assumed to prevent an excessive build-up of LTP in short time. Hence, two blocks of rTMS/iTBS might not induce further facilitation because the LTP degree is in the threshold for inducing further synaptic plasticity (LTP-like effects) [7]. Such a metaplastic effect might explain why two blocks of iTBS did not lead to further increase of excitability. However, the finding that iTBS1800 caused an additional increase in corticospinal excitability can only be explained by overcoming the homeostatic threshold for inducing LTP-like synaptic plasticity after multiple

stimulations. In this study, we observed that longer duration combination of iTBS and FES simultaneously resulted in further facilitation of corticospinal excitability. Both the descending commands from iTBS and activation of afferents input from FES at the same time may be important to explain the results compared to iTBS1800 pulses alone aftereffect from previous studies [6].

In conclusion, our preliminary results provide an indication that the efficiency of iTBS with synchronous FES for enhancing corticospinal excitability can be increased by applying a large number of stimuli, which is equivalent to increasing the stimulation duration. These preliminary results will be important to lead the design of new training and rehabilitation paradigms towards improvements motor performance for individuals with movement impairments.

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Mapping the Motor Networks in the Spinal Cord: Investigating the Safety for Future Research in Humans

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Abstract: *The overall goal of this study was to develop and test the safety of a method for mapping the locomotor networks that may be used in humans in the future. Adult Yucatan pigs were divided into experimental and sham control groups. The experimental group received pial cuts and electrode insertions in the spinal cord while the sham control only received pial cuts. Reflexes and walking kinematics were recorded and compared pre and post intraoperative testing. Similar balance and gait deficits were seen in both groups following surgery, but both groups except for one pig (experimental group) returned to baseline balance and walking abilities by the end of the 4 week period post-surgical testing period. Immunohistological assessments of the spinal cord extracted post-mortem showed very little visible damage from electrode insertions; however, larger damage was present in the dorsal region of the cord associated with pial cuts. The findings suggest that intraoperative stimulation using penetrating electrodes is potentially a safe procedure for mapping in humans but a less damaging approach is required for the pial cuts.*

Keywords: *locomotor networks, lumbosacral spinal cord, intraoperative safety*

Introduction

Epidural spinal cord stimulation neuromodulation has been proposed as a solution to treat pain since the 1960s based on the gate control theory put forth by Melzack and Wall [1]. More recently, neuromodulation has been proposed as a means to restore standing and walking following spinal cord injury [2,3]. Results to date have shown some promise; however, more direct access to the

locomotor networks in the lumbar cord could generate substantially longer distances of weight-bearing over-ground walking [4]. The locomotor areas that reside in the ventral horn of the spinal cord lumbar enlargement have been successfully mapped in preclinical models [5,6]. The goal of this study was to develop and test the safety of a mapping procedure for mapping the locomotor networks in large animal models, and eventually in humans in the future.

Methods

Platinum-iridium microelectrodes (125µm in diameter) approved for use in neurosurgical procedures were inserted into the lumbar spinal cord. A spinal stereotactic frame was used to advance the microelectrode to different locations in the cord under ultrasound guidance [7]. A total of 11 adult Yucatan pigs (45-55kg) were used in the study and were divided into two treatment groups. The experimental group received small cuts to the pia mater to aid in electrode insertion without causing dimpling, followed by 8 to 12 electrode insertions on one side of the spinal cord. The sham control group only received the pial cuts. Prior to surgery, all 11 pigs underwent kinematic and reflex testing. Kinematic analysis included motion capture while the pigs were walking, and reflex testing included the panniculus, withdrawal, and perineal reflexes. Following the surgery, the pigs were given analgesics to ensure a comfortable recovery for at least 2 weeks. Four weeks post-surgery, reflexes and kinematic data were collected again. The pigs were then euthanized and their spinal cords were removed for immunohistochemical analysis.

Results

During the recovery period, transient deficits were seen in both treatment groups; the degree of deficits were similar between both the experimental and sham control group. By 4 weeks post-surgery, all pigs except for one in the experimental group, had returned to baseline for their reflexes. Their walking kinematic data pre- and post-surgery were also similar. Immunohistochemical results showed negligible damage caused by the electrode insertions; however, the pial cuts showed notable disruption to the dorsal surface of the spinal cord.

Discussion

Despite the invasiveness of the surgical procedure, lasting functional deficits were not seen in the movement parameters examined (reflexes and kinematics). Interestingly, insertion of the relatively large diameter microelectrodes also did not appear to cause lasting damage. However, a less invasive technique is required for the pial cuts. Taken together, intraoperative insertion of electrodes appears to be a safe technique for mapping the locomotor networks in the lumbar spinal cord.

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AGONIST-ANTAGONIST MUSCLE CO-CONTRACTION TORQUE IN HYBRID-DYNAMIC MOVEMENT

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Abstract: Synchronization of exoskeleton motor driver with neuromuscular electrical stimulation requires initial determination of functional electrical stimulation (FES) intensity level of agonist and antagonist muscle effect on knee joint torque. FES-induced knee joint torque was measured on 3 paraplegics using dynamometer. The stimulated quadriceps and hamstrings which produced combined flexion and extension moment of the knee were performed simultaneously with different level of current intensities to determine the function of agonist and antagonist muscle effect. Results showed that FES-induced torque produced by all subjects were insufficient even with their highest tolerable intensities they can bear. From the torque-curve diagram, muscle fatigue were present between each trial thus make FES feedback control crucial in the systems. Total joint torque of paraplegic SCI subject during standing and walking should be further simulated to determine the required motor power to compensate for the insufficient FES-generated torque. This study had contributed in the actuator specification determination for the SCI hybrid FES exoskeleton system intended for dynamic movement.

Keywords: Torque generation, FES-induced torque, paraplegic, PDF file

Introduction

Exoskeleton system with functional electrical stimulation (FES) has been used to restore the walking ability for neurological defect patient, especially for the incomplete spinal cord injury. This combination of system always be known as the hybrid neuroprosthesis. Powered exoskeleton system are needed to generate an active torque for joint movement and the FES system helps in reducing the motor power consumption and the actuator size of the mechanical system. Moreover, the use of FES contributes to therapeutic benefits for SCI patients [1]. In the study of efficacy of the hybrid system, result had shown that to have a sufficient torque of the knee, the powered exoskeleton without FES need double mechanical energy per movement rather than the exoskeleton with the FES [2]. Nevertheless, the mechanical structure of exoskeleton and electrical stimulation function must be synchronize to have an effective walking gait for spinal cord injury. The hybrid technologies can be classified into two, which are the system that consist of FES with passive exoskeleton or the ones with FES as the actuated joint exoskeleton [3]. The first type of

hybrid technologies are highly depend on the FES system in produce joint torque to create walking movement, while it mechanical exoskeleton only act as joint moment dissipating device. The exoskeleton can reduce the onset of muscle fatigue by supporting standing phase as it eliminate the stimulation on the quadriceps muscles and also supporting body weight [4]. However powered joint exoskeleton added the ability for the system in shortening the activation of FES as it produces torque, generating complete gait while minimizing muscle fatigue effect.

This study aims to determine the extent of co-contraction torque dynamics between agonist and antagonist muscles induced by FES intended for sit-to-stand and gait movement.

Methods

Four individuals with spinal cord injury consented to participate in this study. Ethical approval to conduct this study was granted by the University of Malaya Medical Ethics Committee (Approval No: 1003.14(1)). They performed isometric muscle contractions induced by functional electrical stimulation (FES) at 30° knee flexion angles on a Dynamometer. Electrical stimulations were applied to both Hamstring and Quadriceps muscle at different level of frequency and current intensity at the same time, and the nett muscle torque produced were been measured. The activation of FES and dynamometer were done at the same time to get the durations of muscle response respect to the electrical stimulations.

Electrical Stimulation: Four surface electrodes (rectangular self-adhesive electrodes, 50 x 130 mm) were placed on knee extensors and flexors, i.e. Quadriceps and Hamstrings. Frequency and pulse width were set to 35 Hz and 350 μ s respectively in every test. This low stimulation frequency and shorter pulse width was chosen to reduce muscle fatigue [5]. The manipulative parameter is the stimulation amplitude which are the current and voltage. Five levels of amplitude intensity was chosen individually by doing some test to the patient in finding the comfortable and tolerable stimulation level for every person. The stimulation for each test person depending on their pain sensitivity.

In finding the highest intensity that the subject can tolerate, muscles were stimulated from low level and increase it until the subject feel pain. This method can be done as all subjects involved are SCI in group AIS C and D, which the sensory still preserve. While for the lowest intensity, FES stimulate the muscle with a very low level intensity and increase it until

some vibration can be feel on subject's muscles. These methods was been done when the subjects were sitting on a chair with 30° knee flexion for checking quadriceps level, and during standing with one leg (tested on the unground leg) for hamstring muscles. The 30° flexion was to ensure the safety against knee hyperextension. Medium, low and high level intensity were set with the value between the lowest and the highest intensity.

All subjects underwent all 5 tests, with each test repeated three times. To avoid any bias to the test order effect, the test order for each subject were randomized. A 3 minutes recovery period between trials been done to reduce the risk of muscle fatigue. Direction movement was set to 'Away' (knee extension) and 'Toward' (knee flexion) as expected movement base on the level of stimulation for both quadriceps and hamstrings muscles. Test 3 and 4 that have the same level of intensity undergo both Toward and Away setting.

Table 1: FES intensity level targeted to Quadriceps and Hamstring for each test.

Test	FES intensity level	Movement Direction	Ratio of Quads:Hams
1	The highest	Lowest	5:1
2	High	Low	4:2
3	Medium	Medium	3:3
4	Medium	Medium	3:3
5	Low	High	2:4
6	The lowest	The highest	1:5



Figure 1: The experimental setup of FES-induced torque data collection by using Biodex Pro 4 Dynamometer and Reha Stim FES. Subject was secured on adjustable chair with his shank in 30 degree knee flexion by dynamometer attachment for isometric test.

Torque Measurement Collection: The test was done just for one side leg at once as the dynamometer only have a single level arm. After setting up the FES and dynamometer systems on subjects, first test were done with 3 times trial. The FES and dynamometer were activated at the same

time and torque readings in real-time were observed from the curve graph display on the Biodex screen. The stimulation continued until fatigue muscle graph pattern present. This pattern can be know when the graph were gradually decrease from the highest torque reading which known as the peak torque. Tests ended and FES inactivated when the graph does not show any increment after dropped from peak value. The mean peak torque values of each test and its standard deviation were calculated. Actual peak torque value calculated as follows;

$$\text{Actual Torque} = \text{Peak Torque with FES} - \text{no FES Torque} \dots (1)$$

Model Parameterization: To confirm the sufficiency of FES-only activation in performing sit-to-stand and walking, the movement was simulated using ADAMS. Gait mechanism requires sit-to-stand movement to start with, which are largely contributed by the contraction of muscles around the lower limb joints. For hybrid neuro-prosthesis users, primarily paraplegic spinal cord injury patients, the force to produce the joint moment depends on internal forces that are created by FES stimulations on specific muscles and the external forces from exoskeleton joint motor power. The range value of internal forces by certain FES current intensities to targeted muscles was derived from the FES-evoked co-contraction experiment with the users using Biodex dynamometer. For external force parameter, it need to be calculated and simulated before setting up on the motor actuator with force power which need to compensate for the insufficient FES-evoked internal force.

Human models was built in ADAMS simulation software based on subject's Body Segment Parameters (BSPs). It include the length, mass, and circumference of each body segment. Body segment length were obtained by measuring on the subject's body part and the segmentations were divided by using bony landmark of respective segment as it is more precise and easy to get rather than separating it from joint axis to another joint axis [6]. The segment parameters used to create human model of each subject was measured the formula of mass segment is as follow;

$$\text{Segmental Mass} = \text{Mass percentage} \times \text{Body mass} \dots (2)$$

From the measurement and calculation mass of each segment, a model had been created in ADAMS Software (ADAMS View). For the sake of simplicity, frustum approximate geometrical shape are used to indicate each segment by knowing the length, biggest circumference and smallest circumference of segments that had been measured from the subject. In order to draw 3D model, length segment and small/large radius of each geometrical frustum need to be known. Model initially was drawn in standing position and modified to be in sitting position as illustrated in Figure 2. The created virtual model consist of only the legs and trunk, but the mass of upper part of body is include to the mass of the trunk.

$$\text{Frustum Radius} = (\text{Measured circumference}) / 2\pi \dots (3)$$

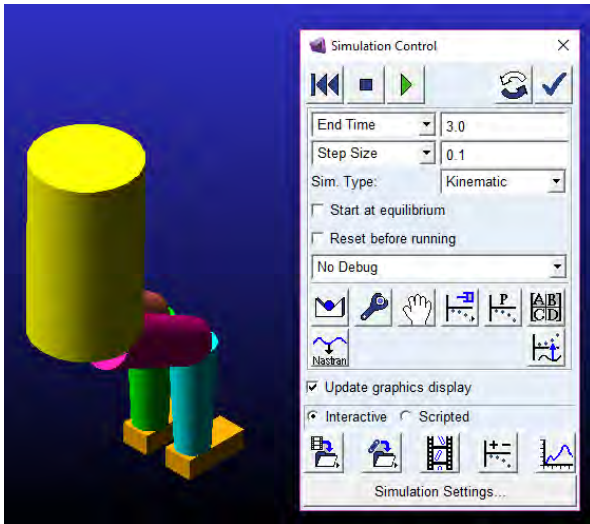


Figure 2: Simulation of sit-to stand movement in ADAMS View

The mass and moment of inertia of each segment need to be set before simulate the dynamic analysis. The use of geometric shape for each segment made it possible to calculate the dynamic moments of inertia [7]. It was automatically been set in ADAMS View after drawing of each geometrical shape which known as 'cm marker'. The direction of these marker shows the orientation of inertial properties.

Model Movement: Using ADAMS dynamic simulation, angular velocities for each joint (were set in order to create joint movements. Some study had provided a dataset of joint angular velocities of hip, knee and ankle joint during all gait phases which is correspond to gait speed. In this simulation, gait speed of 0.40-0.59 m/s was selected and implemented a the angular velocities [8] in ADAMS software. This range of gait speed was selected as we want to have a close targeted simulation results of torque in each joint at least it can fulfill the minimum required normal speed of gait.

To estimate the amount of power that should be produced by the exoskeleton motor actuator, the torque produce by the FES-evoked force should be based on the knee torque profile of the normal gait and the moment created from the ground reaction force. If the maximum torque reading of the FES-evoked force is higher than the normal walking, the antagonist force from motor actuator are needed to reduce the torque reading to avoid over flexion/extension at the joint. However, if the torque produced by the FES-evoked force is lower than the normal torque that is required, motor actuator should be set to generate the same agonist force to complete the insufficient torque.

Results

FES-evoked co-contraction torque revealed a distinct pattern in all subjects.

FES-induced joint torque measurement

Peak Torque: Peak torque reading of each trials for subject 1 were presented in Table 2 as an illustration to the paraplegic muscles' responses to FES. The trend in torque

changes with different co-contraction levels are presented in Figure 3. The maximum torque produced was 40 N.m flexion or extension and activation of antagonist contraction could modulate the amount of nett torque produced. This however was deemed still insufficient to lift the body up during sit-to-stand movement and are more likely to be useful in maintaining upward body posture throughout gait. Gait propulsion may require larger and finer-tuned stimulation to produce the desired power profile, considering the required joint angular speed.

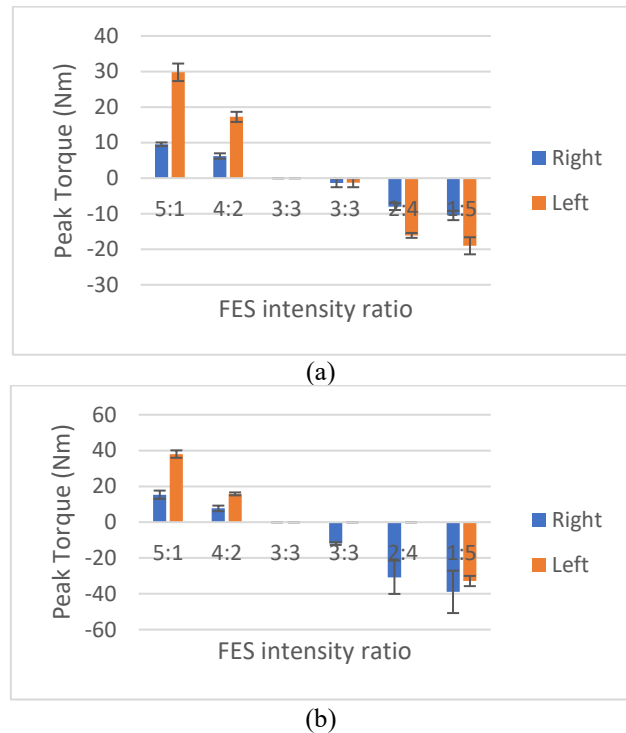


Figure 3: Average peak torque for both right and left legs for (a) Subject 1 and (b) Subject 2. Positive x-axis is for knee extension movement and negative x-axis is for knee flexion.

Dynamic analysis from virtual simulations

Kinetics and kinematics analysis of joint, moment of the bodies in the ADAMS View simulation are visualised in the ADAMS Post-processor Software. Stand-to-sit maneuver was simulated as it is the movement that is required to start gait and requires the highest torque. Result include force and joint torque which the important analysis for setting up joint parameters in exoskeleton systems.

JOINT 10, i.e the point connecting the foot to the ground, which is the point below the foot component having the highest force as all segment weight acting on these two points. The max value of JOINT 10 is equal to total of segment weight divided by 2 (402.99 N). The other values of joint force can be used as material and design selection of the mechanical joint and actuator of the exoskeleton device.

The maximum hip and knee joint torque value is 205.02 Nm and 317.30 Nm respectively. The value is increasing by the end of movement because the movement arms of the

joint is also increase. This happened is when in sitting position, center of mass is shifted from the y-axis of the fixed joint between the foot to the ground.

Table 2 shows the maximum reading of force and torque at each joint. At least 300N.m is required at knee joint to perform the most crucial movement in gait initiation, which is sit-to stand. 200 N.m is required at the hip joint. Ankle joint does not have any joint torque as we fixed it at 90 degree position to animate the Knee Ankle Foot Orthosis (KAFO) on the exoskeleton.

Table 2: Maximum reading of dynamics analysis results during stand-to-sit motion

Real part	Bodies/Connector in ADAMS	Force (N)	Torque (N.m)
Hip joint	JOINT 3 & 7	232.04	205.02
Knee joint	JOINT 2 & 6	352.23	317.30
Ankle joint	JOINT 12 & 13	392.23	-
Ground	JOINT 11 & 10	402.99	-

Discussion

FES-induced torque produced from all subjects were insufficient even with their highest tolerable intensities that they can bear. Thus to minimize the force by motor actuator in achieving desired knee joint torque, the highest intensities was simulation to be applied to the subject when wearing the hybrid neuro-prosthesis. Next, motor control loop might be the suitable feedback in maintaining the functional knee joint torque in creating gait. Motor actuator power were decided to regulate the desired joint torque when FES cannot provide sufficient torque caused by muscles fatigue or caused by any other uncertainty and disturbance.

Resting period between each trial need to be set before starting the test and it is automatically started after the end of contraction period which had been set to 30 seconds. Nevertheless, muscle strength is different for every person thus muscle contraction due to the FES were varies for every subject. Most FES-evoked contraction take below 30 seconds, with the average duration recorded from our experiment to be around 20 seconds. The remaining 10 seconds were added up for resting period. Thus, all set of trials could not have the same resting period.

In future work, the actual torque from motor actuator and muscle stimulation intensities are set depending on the prototype joint properties and actuator specification. The performance of prototype should be tested and personalised for the identified subject or SCI user in different dynamic movement including in normal walking movement and sit-to-stand maneuver.

Acknowledgement

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ELECTROMYOGRAPHY-BASED CADENCE CONTROL OF FUNCTIONAL ELECTRICAL STIMULATION CYCLE

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Abstract: Motorized functional electrical stimulation (FES) cycling is a promising rehabilitation strategy for those with neurological injuries and disorders. However, the cycle's operation is often restricted to a predetermined cadence (i.e., speed) or trajectory, especially when investigating closed-loop control of the cycle's motor and rider's muscles. In this paper, a human is placed in the control loop and the cycle's cadence is adjusted real-time using measured electromyography (EMG) signals from the biceps muscle groups. While the rider's leg muscles are stimulated with FES and tasked with pedalling the cycle at the time-varying cadence, the cycle's motor is actuated using an admittance controller, and emulates an assist-as-needed controller. Both the muscle and motor controllers were developed using Lyapunov stability analyses to ensure rider safety and stable human-robot interaction. To promote user engagement, the rider is challenged with volitionally modulating their EMG signal to reach various targets (i.e., cadences). Results are included on four participants without neurological injuries to show the efficacy of the proposed approach. The cadence and admitted cadence tracking error were regulated to the average of 1.47 ± 5.16 RPM and -0.02 ± 0.33 RPM, respectively.

Keywords: EMG, FES, Cycling, Control, Robot

Introduction

Worldwide, there are millions of people suffering from neurological disorders such as traumatic brain injuries (TBI) and spinal cord injuries (SCI) [1], [2]. These injuries can often lead to inconveniences in performing day-to-day tasks due to deterioration of the lower limb muscles' mobility, strength, endurance, and coordination. To overcome such difficulties, various rehabilitative and therapeutic techniques focusing on muscle activation have been suggested. Among them all, neuromuscular electrical stimulation (NMES) methods are proven to be highly effective by inducing artificial muscular contractions using symmetric and biphasic stimulation currents [3], [4]. More specifically, functional electrical stimulation (FES) cycling is an effective form of rehabilitation training for people with SCI which has been shown to increase the lower-limb muscles' endurance without spasticity [5], [6]. FES cycling, as a rehabilitation method for people with neurological injuries, can still be developed in multiple ways since there are many different outstanding challenges, especially when it comes to control and human-robot interaction. One of the challenges of using FES cycling for rehabilitation purposes is the use of predefined cadence trajectories [7] – [9] since it restricts the rider's movement and cadence. Additionally, it has been shown

that rehabilitation therapies may lead to boredom due to failure in engaging the participants in the training process [10]. In an effort to modulate the movement of robots, and specifically rehabilitation robots, electromyography (EMG) has been previously suggested and implemented. For example, EMG has been utilized to issue commands and control wheelchairs, ankle robots, powered exoskeletons, and even FES cycles [11] – [14].

In this paper, a previously developed closed-loop cadence/admittance control algorithm [15] is implemented on an FES cycle, however, a novelty of this work is that the controller is now used to track a time-varying cadence generated from volitional EMG signals, instead of a fixed nominal cadence. Furthermore, user involvement is encouraged because the EMG signals must be voluntarily modulated through contraction of the biceps brachii muscles to follow various cadence targets. This work combines FES with robotics and examines the feasibility of using volitional muscle contractions to control other muscle groups in a game-like fashion. The proposed approach is designed to promote intensive and highly involved rehabilitation sessions. Experiments conducted on four participants with no neurological injuries are included to verify the efficacy of the applied approach.

Methods

Hardware/Software. Experiments are conducted with a recumbent cycle (Terratrike) equipped with an encoder (US Digital H5-5000-IE-S) used to measure position and cadence, and a powermeter (SRM Science Road) used to measure the interaction torque between the rider and cycle. A 350-Watt DC electric motor (Monster Scooter Parts) is attached to the cycle's drive chain and controlled with a servo drive (AMC). The encoder, powermeter, and servo drive interface with a desktop computer through a Quanser data acquisition device (DAQ). The desktop computer is running Windows 10 and all programming is implemented in MATLAB/Simulink. The rider's feet are attached to the cycle's pedals using orthotic boots, which also maintain sagittal alignment of the legs. The rider's quadriceps and hamstrings muscles are activated using electrodes (PALS) and a neuromuscular electrical stimulator (Hasomed, EnableMe) with symmetric and rectangular pulses at 60 Hz with current amplitudes of 90 mA for quadriceps and 70 mA for hamstrings. The EMG signals were acquired using EMG sensors (MyoWare) and read using the DAQ. An emergency stop is able to the rider and cycle. Additional details of the FES cycle are available in [15].

Controllers. To actuate the combined cycle-rider system, separate controllers are needed for the cycle's motor and

rider's muscles. The rider's muscle control input (i.e., pulsewidth) is denoted by $u_h(t): \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}$ and defined as

$$u_h(t) = f(e(t), \dot{e}(t)), \quad (1)$$

where $e: \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}$ denotes a position error defined as

$$e(t) = q_d(t) + q_{EMG}(t) - q(t), \quad (2)$$

where $q_d: \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}$ denotes a (nominal) desired position trajectory, $q_{EMG}: \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}$ denotes the subsequently defined generated EMG position trajectory, and $q: \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}$ denotes the measured cycle crank's angular position. In (Eq. 1), $\dot{e}: \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}$ denotes the time-derivative of (Eq. 2), i.e., the cadence error. The cycle's motor control input (i.e., amperage) is denoted by $u_r(t): \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}$ and defined as

$$u_r(t) = f(\xi(t), \dot{\xi}(t), \tau_{int}(t)), \quad (3)$$

where $\tau_{int}: \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}$ denotes the interaction torque between the cycle and rider, and $\xi: \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}$ denotes an admittance position error defined as

$$\xi(t) = q_d(t) + q_{EMG}(t) + q_a(t) - q(t), \quad (4)$$

where $q_a: \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}$ denotes an admitted position trajectory. Note, the admitted trajectory is a function of the interaction torque, i.e., $q_a = f(\tau_{int})$, and emulates a low-pass filter of the interaction torque. In (Eq. 3), $\dot{\xi}: \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}$ denotes the time-derivative of (Eq. 4), i.e., the admitted cadence error system. Full details of the controllers in (Eq. 1) and (Eq. 3), in addition to the dynamics and stability analyses, are available in [15], though the controllers did not utilize any EMG signals.

Electromyography. The novelty of the proposed approach is the incorporation of EMG into the closed-loop controllers in (Eq. 1) and (Eq. 3), and the error systems in (Eq. 2) and (Eq. 4), allowing the rider to volitionally control the cadence of the FES cycle without their hands. To generate the modified cadence trajectory, i.e., \dot{q}_{EMG} , two EMG sensors were used; one to accelerate the cycle, and one to decelerate the cycle. The modified EMG trajectory was generated according to

$$\dot{q}_{EMG}(t) = \int_{t_0}^t h_1(V_{EMG,1}(\psi)) - h_2(V_{EMG,2}(\psi)) d\psi \quad (5)$$

where $V_{EMG,1}, V_{EMG,2}: \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}_{\geq 0}$ denote the raw EMG voltages from the two sensors, and h_1, h_2 denote processing algorithms consisting of rectifying, filtering, and amplifying the raw EMG voltages. The modified EMG position of the cycle, i.e., q_{EMG} , was generated by integrating (Eq. 5). Accordingly, the rider could accelerate the cycle by increasing $V_{EMG,1}$ and decelerate the cycle by increasing $V_{EMG,2}$. The rider increases these voltages by volitionally contracting the muscle group to which the sensors are mounted.

Experimental Procedure. To assess the feasibility of the proposed approach, experiments were conducted for 240 seconds on four participants, one male and three females, without neurological injuries, aged between 24 and 35. Only Participant A had prior experience with FES cycling. The rider's muscles and cycle's motor were actuated using the controllers in (Eq. 1) and (Eq. 3), respectively. Without

loss of generality, the nominal desired cadence was selected as 40 RPM, i.e., $\dot{q}_d = 40$ RPM. To promote user involvement, the rider was challenged with modulating their combined EMG signal in (Eq. 5) to achieve various cadence targets. Throughout the experiment, these targets were selected (in order) as 35, 45, 30, 50, 25, 55, and finally 40 RPM, so that they were alternating around the nominal cadence of 40 RPM with increasingly larger steps. When the rider successfully achieved the targeted cadence (by staying within 3 RPM of the target for 5 consecutive seconds), the target cadence switched to the next value.

The rider was instructed to avoid pedalling the cycle volitionally and was only shown a plot of the target cadence, along with the output from (Eq. 5), and attempted to align the two. All experiments are approved by the University of Alabama IRB #20-005-ME.

Results

During experiments, it was observed that the electromagnetic noise generated by the brushed DC motor on the cycle was negatively affecting the signal from the EMG sensors worn by the rider. Therefore, a modification was made to the experimental procedure so that the EMG sensors were instead worn by a member of the study staff, away from the motor, to generate the signals in (Eq. 5). Despite relocating the EMG sensors, the following results demonstrate the feasibility of the control algorithm and the ability of an individual to modulate the cycle's cadence using volitional EMG signals. Further details are provided in the Discussion section and solving the electromagnetic interference is left as a future work.

Numerical results on the measured, admitted, and generated EMG cadence, as well as cadence errors and control inputs of the FES cycle are reported in Table 1.

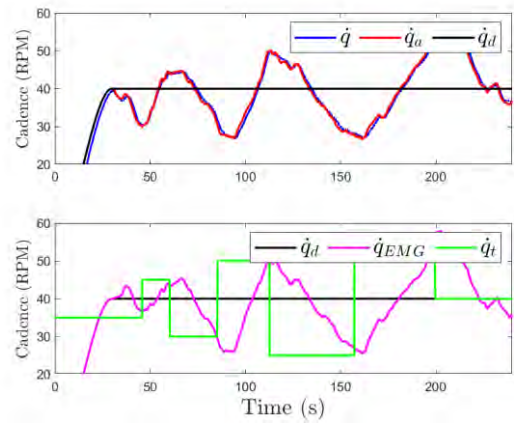


Figure 1. (Top) Participant A's cadence tracking results for the cycle's motor. The cycle's motor is tasked with driving the cycle's cadence \dot{q} toward the admitted cadence \dot{q}_a , which is tied to the nominal desired cadence \dot{q}_d . (Bottom) Participant A's cadence results for the rider and their muscles. The rider is tasked with driving the cycle's cadence \dot{q} toward the target cadence \dot{q}_t through volitional muscle contractions. The rider's muscles are tasked with driving the cycle's cadence \dot{q} toward the generated EMG cadence \dot{q}_{EMG} . A 1.5 s moving average filter (i.e., approximately one crank cycle at 40 RPM) was applied to plots for visual clarity.

Table 1: Experimental results, reported as average \pm standard deviation

Participant	\dot{q} (RPM)	\dot{q}_a (RPM)	\dot{q}_{EMG} (RPM)	ξ (RPM)	\dot{e} (RPM)	u_r (A)	u_h (μ s)
A	36.76 ± 11.04	-0.42 ± 1.87	-0.15 ± 7.16	-0.02 ± 0.59	0.64 ± 7.57	2.74 ± 0.55	52.04 ± 18.64
B	40.11 ± 4.02	-0.32 ± 2.45	0.42 ± 5.03	-0.04 ± 0.68	-0.11 ± 4.02	2.68 ± 0.56	45.88 ± 27.17
C	39.49 ± 5.00	-0.29 ± 0.54	-0.22 ± 5.15	-0.00 ± 0.50	0.51 ± 5.00	2.71 ± 0.46	31.61 ± 11.33
D	35.15 ± 4.06	-4.93 ± 1.71	0.07 ± 4.94	-0.01 ± 0.73	4.85 ± 4.06	2.82 ± 0.57	59.53 ± 22.75
Mean	37.88 ± 6.03	-1.49 ± 1.64	0.03 ± 5.57	-0.02 ± 0.33	1.47 ± 5.16	2.74 ± 0.54	47.27 ± 19.97

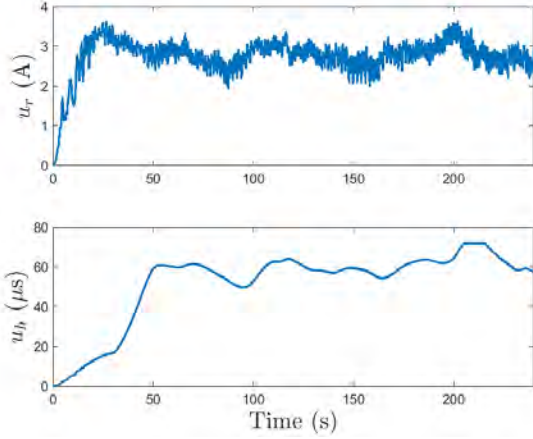


Figure 2. (Top) Participant A's control input delivered to the cycle's motor. The amperage is determined by the motor controller in (Eq. 3). (Bottom) The stimulation pulsewidth delivered to Participant A's muscles. The pulsewidth is determined by the muscle controller in (Eq. 1). The stimulation frequency is 60 Hz, and the amplitude is set to 90 and 70 mA for the rider's quadriceps and hamstring muscles groups, respectively. A 0.5 s moving average filter was applied for visual clarity.

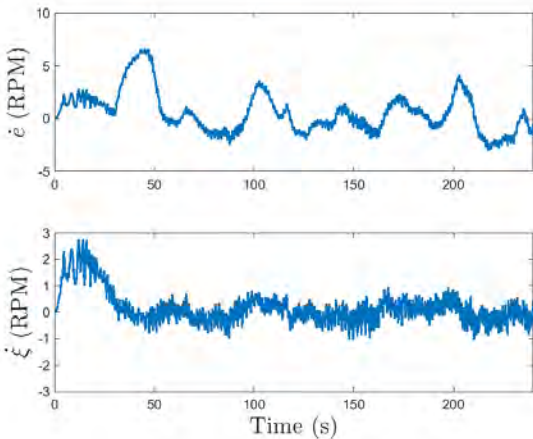


Figure 3. (Top) Participant A's cadence error, \dot{e} , and (Bottom) admittance cadence error, ξ . A 0.5 s moving average filter was applied to plots for visual clarity.

Figure 1 provides details on Participant A's various cadence signals throughout the experiment, Figure 2 provides details on the control inputs delivered to the Participant A's muscles and to the cycle's motor, and Figure 3 provides details on the Participant A's cadence errors.

Discussion

The operation of the FES cycle requires multiple controllers and error systems. Using volitional muscle contractions measured with EMG sensors, the rider (or cycle operator) is tasked with regulating the cadence of the cycle to follow various targets. Simultaneously, the rider's leg muscles are stimulated and actuated with FES to pedal the cycle and achieve the cadence determined by the EMG signals. While the rider pedals the cycle, the attached motor supports the rider with an assist-as-needed control structure (i.e., an admittance controller). The controller operates by measuring the interaction torque between the rider and cycle and then processing it using an admittance filter. The output of the filter is the generated the admitted cadence trajectory, which increases along with the interaction torque. If the rider is unable to achieve the cadence generated by the EMG signals through FES alone (which manifests itself as a torque deficit), the motor will assist them in achieving this cadence by providing supplemental torque through the admittance controller. Conversely, when the rider successfully tracks the cadence trajectory and produces enough torque via FES, the motor neither assists or resists the rider, but only rotates at the desired cadence and matches the rider, i.e., $\dot{q}_a = 0$ and $\dot{e} = \xi$.

As illustrated by Table 1 and Figure 1, the motor was successfully able to regulate the admitted cadence error, ξ , to an average of -0.02 ± 0.33 RPM. The riders were also able to regulate the cadence error, \dot{e} , to an average of 1.47 ± 5.16 RPM. Note, the value of cadence error, \dot{e} , for Participant D is higher in comparison to other participants because of early FES saturation; the input is saturated for both comfort and safety. The effect of saturation may be lessened over time as participants are acclimated with the FES process and their threshold of stimulation tolerance increases. Figure 3 illustrates the cadence error and admitted cadence error for Participant A. While the cadence error presents a larger standard deviation than the admittance cadence error, this is a direct result of the change in the targeted cadences. On Table 1, the cycle's measured cadence also varied significantly as a result of

the accelerations and decelerations caused by following the target cadence trajectories.

Additional details are provided on Table 1 and Figure 2 illustrating the control inputs delivered to the cycle-rider system. Across all participants, the average input to the motor was 2.74 ± 0.54 A and the average pulsewidth sent to the participants' muscles was 47.27 ± 19.97 μ s. Though the same pulsewidth was delivered to the rider's right and left quadriceps and hamstrings muscle groups, it can be amplified or attenuated through control gains, and saturated for user comfort and safety [15].

As previously mentioned, due to electromagnetic interference in close proximity to the motor, a member of the study staff who was not the rider wore the EMG sensors. Despite this fact, the study member was able to successfully modulate their EMG signal to achieve the targeted cadence. The individual wore the two EMG sensors on their biceps brachii muscle groups and volitionally contracted their right and left biceps muscle to accelerate and decelerate the cycle, respectively. Isolating the EMG signal from the electromagnetic noise generated by the cycle's motor was a significant challenge of the current work. Various solutions were attempted including adjusting signal gains and filter parameters in (Eq. 5), selecting new locations/muscle groups for the EMG sensors, and replacing the sensors. Ultimately, the method which provided the best solution was distancing the sensors from the motor itself. Therefore, resolving this issue is an objective of future works. Potential solutions include installing a Faraday cage around the motor, replacing the brushed DC motor with a brushless DC motor, or utilizing EMG sensors which are capable of isolation. Additional future works include expanding the capabilities of the cycle such as using additional physiological signals to control the cadence and operation of the FES cycle (e.g., electroencephalography) and conducting additional experiments with participants with neurological injuries.

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DEVELOPMENT OF AN ANATOMICALLY REALISTIC CERVICAL TRANSCUTANEOUS SPINAL CORD STIMULATION MODEL

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Abstract: Cervical transcutaneous spinal cord stimulation (tSCS) can be used for rehabilitation of upper-limb function of spinal cord injured patients. Rehabilitation effects may be enhanced by selectivity of spinal segments with different electrode configurations. In this study, a realistic tridimensional model of the cervical human body and stimulating electrodes was developed to analyze tSCS selectivity of spinal segments with different cathode configurations. The model includes 47 components developed from MRI geometries and anatomic proportions found in the literature. Finite element method was used to estimate the distribution of electric potential along sensory axon fiber models of C7 and C8 spinal levels for the cathode configured over C6, C7, and T1 vertebral levels. The anode was configured over the anterior neck. The fibers activation thresholds were estimated, and compared across cathode configurations and spinal levels. Our results showed smaller activation thresholds for the cathode configured at T1 compared to C6 for both spinal levels. These results corroborate previous experimental results in human studies. Overall, this study developed and tested an anatomically realistic cervical tSCS model, paving way for future model-based studies.

Keywords: transcutaneous spinal cord stimulation, spinal cord, electrical stimulation, sensory fibers.

Introduction

Cervical transcutaneous spinal cord stimulation (tSCS) has recently emerged as an electrical stimulation technique for the rehabilitation of the upper limb function of spinal cord injured patients [1], [2]. The efficacy of these cervical tSCS rehabilitation protocols was suggested to depend on the activation of Ia-sensory fibers during stimulation [3]. Moreover, selective excitation of spinal segments is indicated to enhance rehabilitation effects after spinal cord injury [4], [5]. In our recent study, the activation of Ia-sensory fibers [6] and selectivity of spinal segments with different cathode electrodes were experimentally demonstrated for cervical tSCS [7]. In particular, more caudal cathode configurations (at T1 vertebral level) preferentially activated more distal hand muscles compared with the cathode configuration at more cranial levels (at C6 vertebral levels), while the anode was configured over the anterior neck [7]. However, further investigations with experimental and computational studies are warranted to corroborate these results.

Computational simulations have been a very important tool for better understanding of mechanisms underlying tSCS at neural levels that are not accessible in experimental

studies with humans [8], [9]. Specifically, computational simulations with finite element method (FEM) and mathematical models of nerve fibers have been used for estimating the activation of sensory and motor fibers during tSCS [8], [9]. This methodology has previously been used to investigate nerve fiber activation during lumbar tSCS. Despite notable differences between cervical and lumbar body anatomy, there are no computational models of cervical tSCS to understand nerve fiber activation at cervical levels.

Considering the experimental results found in de Freitas et al. [7], we hypothesized that the axon fiber activation thresholds will be influenced by different cathode configurations. Specifically, the computational model was used to reproduce experimental conditions of de Freitas et al. [7] for analyzing selectivity of spinal segments with different cervical tSCS electrode configurations. The activation thresholds of sensory nerve fibers at C7 and C8 spinal levels were estimated while the cathode electrode was configured at (i) C6; (ii) C7; and (iii) T1 vertebral levels, and the anode configured over the anterior neck.

Methods

A tridimensional geometry including anatomical structures of the cervical body and cervical tSCS electrodes was developed. The geometry was used for estimating the distribution of electric potential along the trajectories of nerve fibers at C7 and C8 spinal levels with the cathode placed over the C6, C7, and T1 vertebral levels (Fig. 1 and Fig. 2). The activation threshold of each trajectory was estimated and compared across cathode configurations and spinal levels.

Finite Element Method: A tridimensional geometry of the cervical body and cervical tSCS electrode configurations was designed in Inventor Professional 2021 (Autodesk, U.S.A.) based on MRI reconstructed geometry of the “virtual family” [10] and anatomic quantified values found in the literature [11]–[13]. In total, 47 components were designed including: C7 and C8 spinal roots; dorsal and ventral roots and rootlets; dorsal root ganglion; grey matter; white matter; cerebrospinal fluid; epidural fat; vertebral bones (C5, C6, C7, and T1); intervertebral disk (C5-C6, C6-C7, and C7-T1); back muscle; skin; fat; general upper-body; an anode electrode (7.5x10 cm) placed on the anterior neck [6], [7]; and a cathode electrode (5x5 cm) placed over the C6, C7 or T1 spinous processes, consistent to our previous experimental study [7]. It is noteworthy that no adverse events during stimulation were experienced by participants in de Freitas et al. [7] for these electrodes configurations. The geometries of some components are depicted in Fig. 1.

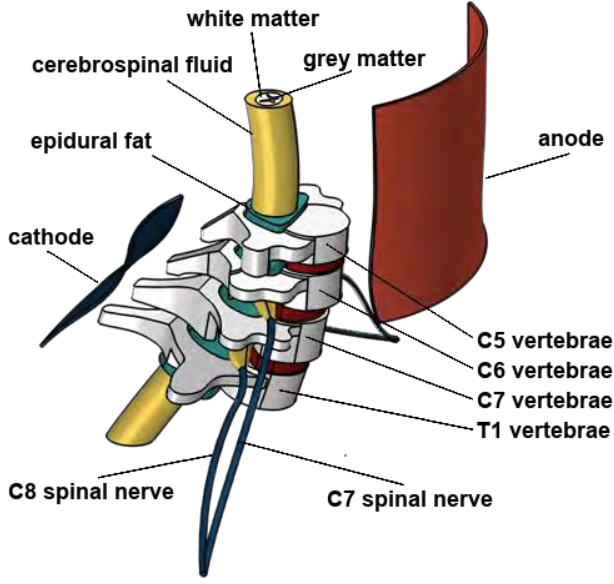


Figure 1: Tridimensional geometry of the cervical spinal cord. The cathode was placed over the C7 vertebra, whereas the anode was placed over the anterior neck.

The geometry was imported in COMSOL Multiphysics v.5.6 (COMSOL Inc., U.S.A.) for FEM computational simulations. The conductivity of each material was assigned according to previous spinal cord stimulation computational studies [8], [9], [14]. The conductivity of each material is shown in Tab. 1. The anisotropy of the white matter and muscle were implemented with the Curvilinear Coordinates interface available in COMSOL [15]. The materials were considered as purely resistive, and a quasi-stationary approximation was assumed for estimating the electric potentials [16].

The geometry was meshed with approximately 13 million tetrahedrons. The Laplace equation (Eq. 1) was solved with the FEM:

$$(\nabla \cdot (\sigma \nabla V))(x) = 0 \quad (1)$$

where V is the electric potential and σ the electrical conductivity. Zero current-flux boundary condition was applied to all external surfaces, except for the largest surfaces of the electrodes. For the cathode electrode, $V = 0$ was adopted. For the anode electrode, normal current density condition was applied such that 1A current was injected [8], [9], [14].

Sensory nerve fiber model: The trajectories of nine nerve fibers were defined for each spinal level (C7 and C8). Their trajectories were defined from the right spinal nerves at the brachial plexus level until the grey matter, as shown in Fig. 2A. In particular, the trajectories differ at the interface between the dorsal rootlets with the white matter, where nine different angles and curvatures were defined. Along each fiber trajectory, the electric potential obtained from the FEM simulations was input in a nerve fiber model. The nerve fiber model described by Gaines et al. [17] was used for simulating the activation of the sensory fibers. This model is a modified version of the

myelinated axon fiber model developed in McIntyre et al. [18], also accounting for conductivity difference of sensory fibers [19]. The model was implemented with the NEURON interface [20].

Table 1: material conductivities used for simulating each component [8], [9], [14]. Legend: T: transversal; L: longitudinal

Component	Conductivity (S/m)
Grey matter	0.276
White matter	L: 0.6; T: 0.083
Root and rootlets	0.1432
Dorsal root ganglion	0.1432
Cerebrospinal fluid	1.7
Epidural fat	0.04
Intervertebral disks	0.6
Vertebral bone	0.02
Muscle	L: 0.5; T: 0.08
General body	0.25
Skin	0.0025
Fat	0.04
Electrodes	0.01

Simulation: For each cathode configuration (C6, C7, and T1), the nerve fiber activation thresholds at C7 and C8 spinal levels were measured (Figure 2B). The nerve fibers activation thresholds, quantified in terms of the stimulation current (mA), were estimated with a bisection algorithm for a 2 ms width pulse. The nerve fibers were simulated with 15 μm of diameter to simulate Ia-sensory fibers.

Statistics: A within-subject two-way ANOVA was performed for comparing the activation thresholds across C6, C7, and T1 cathode configurations (*cathode*) and C7 and C8 spinal levels (*spinal level*). Since significant interactions were found, one-way ANOVA was performed for each factor. Post-hoc multiple comparisons were conducted when significant results were found with Bonferroni correction factor. Parametric tests were used since the data were normally distributed. Statistical tests were performed with SPSS (IBM, Armonk, NY) with significance level $\alpha = .05$.

Results

Since interactions (*spinal level* vs *cathode*) was shown ($P < .001$) for the two-way ANOVA, follow-up analyses with one-way ANOVA were performed for each factor separately. One-way ANOVA showed statistically significant differences for *spinal levels* for all cathode configurations (C6: $P < .001$; C7: $P < .001$; and T1: $P < .001$). Moreover, one-way ANOVA showed statistically significant differences for *cathode* for both spinal levels (C7: $P < .001$; and C8: $P < .001$). In Fig. 3, post-hoc multiple comparisons between activation thresholds of two axon fibers are shown. These results show higher activation thresholds for sensory fibers when the cathode electrode was placed over at T1 compared with C6, for both C7 and C8 spinal levels. Furthermore, activation thresholds at C7 were smaller than C8.

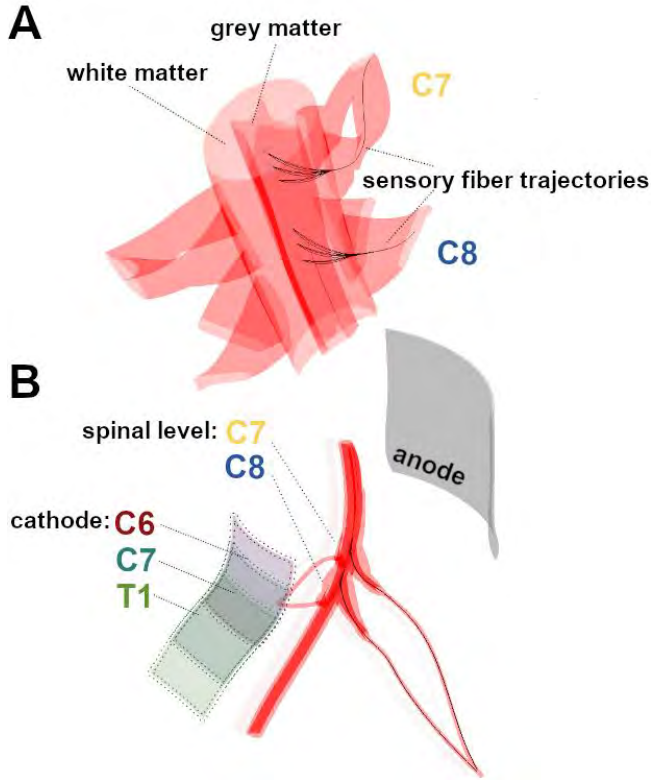


Figure 2: (A) Trajectories of sensory fibers entering the spinal cord from the C7 and C8 dorsal rootlets. (B) Simulation of 3 cathode configurations (C6, C7 and T1), while the anode is placed over the anterior neck.

Discussion

In the current study, a realistic tridimensional model of cervical tSCS was developed for analyzing the selectivity of spinal segments with different cathode electrodes. Our results showed lower activation thresholds for T1 cathode location compared with C6, for both C7 and C8 spinal levels. Moreover, the activation thresholds of the nerve fibers at C8 were higher compared to C7.

In the experimental results obtained by de Freitas et al. [7], distal hand muscles were preferentially activated with the cathode configured at T1 vertebral level compared with C6, while the anode was placed over the anterior neck. Based on the organization of the distal upper-limb muscles motor pools at more caudal levels of the cervical spinal cord compared with proximal arm [21], this result suggested preferential activation of more caudal spinal segments with the cathode placed at T1 vertebral level compared to C6. Likewise, the results obtained in the current computational stimulation study show selectivity of two spinal levels with different cathode configuration, which corroborate the experimental results by de Freitas et al. [7] at a neural level.

Our results showed a difference between the activation thresholds at C7 and C8 spinal levels, suggesting that nerve fibers at C7 may be exclusively activated during tSCS. This difference may be due to a difference in geometry at

these spinal levels. For instance, the shape of the vertebrae that are bonier at C8 level compared to C7 (c.f., Fig. 1) might have had an effect. Moreover, the curvature of the spinal cord respective to the cathode electrode (c.f. Fig. 1) might also have had an influence on the results. Future studies are therefore warranted to further investigate the effects of these geometrical differences on the activation thresholds.

It should also be noted that the current model is limited to the representation of only a few structures of the cervical body, and should be expanded for more realistic representation of the cervical tSCS. Moreover, regarding the aims of the current study, more spinal levels and electrode configurations (e.g., shapes and sizes) are required to study the selectivity of the cathode location. Motor axons, which are also activated during cervical tSCS [6], [7], should be included for testing of activation of sensory and motor fibers in future studies.

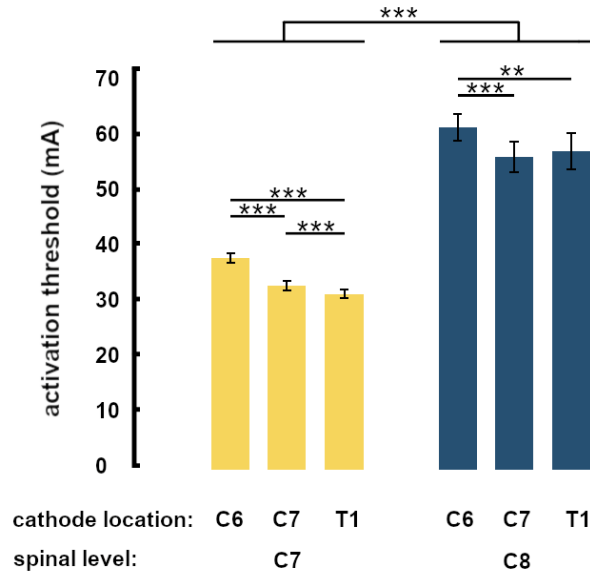


Figure 3: Activation thresholds (mA) averaged from 9 sensory nerve fibers trajectories at each spinal level and cathode location. Vertical bars are corresponding standard errors. Legend: *** indicates $P < .001$, and ** indicates $P < .01$.

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PILOT STUDY ON THE COMBINATION OF ROBOTIC GAIT TRAINING WITH STIMULATION OF THE WITHDRAWAL REFLEX IN PATIENTS WITH SPINAL CORD INJURY

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Abstract: *We present the preliminary results of a pilot study on the safety, tolerance and immediate effects of combining robotic gait training with stimulation of the nociceptive withdrawal reflex in spinal cord injury patients. Two patients with spinal cord injury completed 8 days of the proposed therapy. No adverse effects were observed, the stimulation was well tolerated by the patients and it did not interfere with the robotic therapy. Although some statistical differences between treatment blocks with and without stimulation were obtained for the two patients, the results do not allow to conclude on the effects of the proposed therapy. Along with gathering data from more patients, we plan to investigate the immediate effects of the stimulation along gait cycles, as well as the effects of the stimulation across days of treatment.*

Keywords: *Robotic Gait Training, Lokomat, Functional Electrical Stimulation, Withdrawal Reflex, Spinal Cord Injury*

Introduction

The combination of gait rehabilitation therapy with electrical stimulation-induced nociceptive withdrawal reflexes (NWR) has been successfully used by hemiparetic patients [1] and its combination with Lokomat gait training (LGT) has also been proposed for the same group of patients [2]. LGT makes use of different neurophysiological mechanisms to restore the ability to walk after a spinal cord injury (SCI). SCI patients, who trained with LGT, have larger improvements in walking distance, leg strength, and functional level of mobility and independence than the SCI patients who trained on the floor [3]. A pilot study is currently investigating the feasibility of gait rehabilitation combining LGT therapy with therapy based on the use of the NWR in patients with SCI. This paper presents preliminary results from two patients that have completed the longitudinal intervention.

Methods

Two patients, Patient 1: incomplete SCI, C4 level, AIS: D and Patient 2: incomplete SCI, D6, AIS: D, participated in

this pilot study. Patients read and signed an informed consent. The study was approved by the Ethics Review Board of the Complejo Hospitalario de Toledo and it was conducted in accordance with the Declaration of Helsinki.

The patients participated in eight sessions of robotic gait training in consecutive week days. Each session consisted of: a) five minutes of LGT, b) followed by 20 minutes of LGT combined with activation of the NWR, synchronized with the gait cycle, to facilitate the swing phase, and c) finalized by five minutes of LGT.

To elicit the NWR, 5 electrical stimulation pulses (random duration between 0.5 and 1.5 ms, frequency of 200 Hz) repeated 4 times at 15 Hz [4] were delivered synchronized with the swing phase of Lokomat. The amplitude of the pulses was adjusted individually for each patient to obtain the desired kinematic effect. The cathode (Neuroline 700, Ambu, Denmark Ag-AgCl, 2.63 cm²) was placed on the arch of the foot and the anode (Prim-Trode®, Spain, 5×9 cm) was placed on the dorsum of the foot. The most affected side was stimulated, but in case that there was no difference between the sides, the dominant side was stimulated.

The driving force exerted by Lokomat's motors to drive the hip and knee joints of the patient within the kinematic pattern was sampled at 1 kHz via a NI (PCI-2517) board and stored in a computer via a custom-designed code written in C++.

For each training session, the right hip and knee motor driving forces were segmented using Lokomat's foot-floor contact signal and time-normalized from 0 to 100%. Positive driving forces correspond to joint extension, while negative driving forces correspond to joint flexion. The maximum and minimum driving forces were extracted for each step of the first 5 minutes of training (Block I, no stimulation), the following 5 minutes (Block II, NWR stimulation), and the next 5 minutes after ceasing the stimulation (Block III, no stimulation). The parameters from the eight sessions were grouped and averaged by training blocks. RM-ANOVA with Games-Howell post-hoc test was applied to test differences between blocks, the p-value was set to 0.05.

Results

Both patients completed the eight sessions of robotic gait training. In both cases, the left foot was stimulated. No adverse effects were reported neither patients reported pain or comfort-related issues. Figure 1 shows the mean \pm SD

standard deviation of the maximum Lokomat's driving force for the hip and knee of each patient during joint flexion and extension.

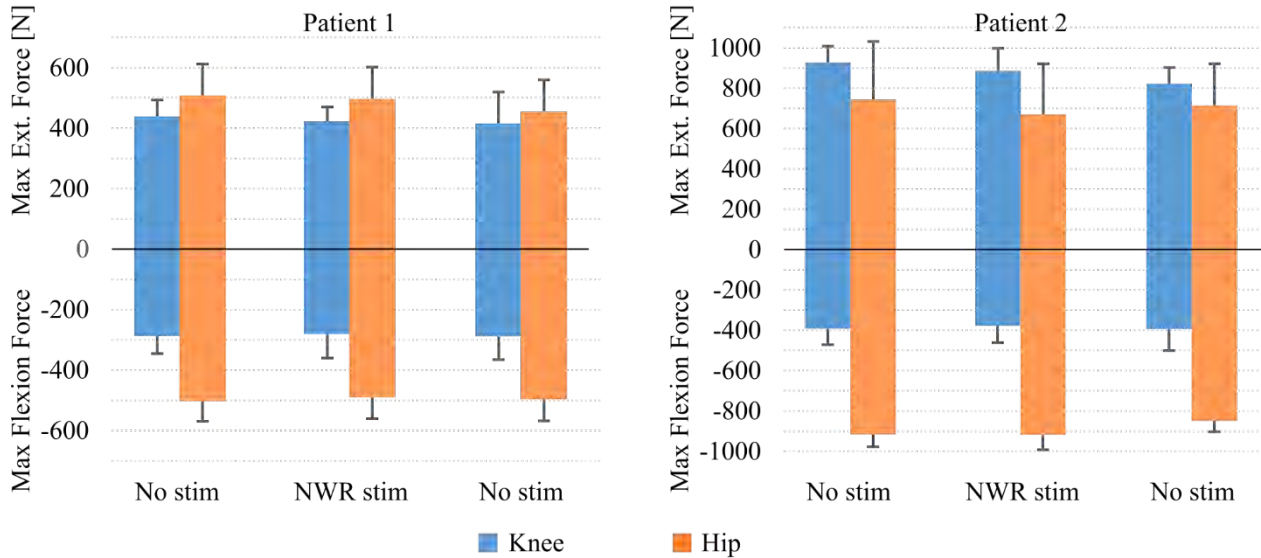


Figure 1: Maximal driving force, necessary to produce flexion and extension of the knee and hip joints for the patients. Positive values correspond to extension. Negative values correspond to flexion. Values are mean \pm SD across sessions, for the three blocks of Lokomat gait training (no stimulation, NWR stimulation, no stimulation).

A significant effect of training blocks was found for the hip and knee joint driving forces for both patients (RM-ANOVA, $p < 0.05$). Post-hoc tests revealed differences in hip and knee driving forces for both patients. Specifically, the knee and hip extension driving force was higher in Block I than in Block II and Block III for both patients, whereas the extension driving force was also higher in Block II than in Block III for patient 1. Differences in hip and knee flexion driving force were observed only in patient 2. Concretely, at the hip, the flexion driving force was minimal in Block III, and at the knee, it was minimal in Block II.

Discussion

In this pilot experience, no pain or comfort issues related to the nociceptive withdrawal reflex stimulation, combined with Lokomat gait training, were reported. Both patients tolerated the therapy and no signs of skin irritation were found at the electrode placement area.

Although several differences in hip and knee driving forces were observed at patient level, the effects of the stimulation remain to be clarified. The decrease in hip and knee extension driving forces across treatment blocks, and particularly in Block III, cannot be solely attributed to the stimulation but it might likely be due to the effect of limb mobilization with Lokomat, which is known to reduce lower limb muscle stiffness [5].

On the other hand, using electrical stimulation to activate the withdrawal reflex, if effective, should affect the flexion driving force, decreasing the force applied by the robot. We have only seen this in patient 2, when analysing knee driving forces for block-averaged gait cycles.

Although the physiotherapist adjusted the stimulation amplitude to obtain a visible kinematic reflex response, our analysis did not show the expected general reduction in Lokomat driving force. We hypothesize that habituation of the reflex response could have happened some cycles after the beginning of the stimulation, and therefore, the effect of the stimulation was not apparent in the block-averaged data. Along with gathering data from more patients, we plan to investigate the immediate effect of the stimulation in the individual gait cycles, as well as the effects of the stimulation across days of treatment.

In conclusion, the combination of robotic gait training with stimulation of the withdrawal reflex seemed to be safe and tolerated by the patients and did not seem to interfere negatively with the Lokomat gait training. However, the limited amount of data does not allow to conclude on the effects of the treatment.

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A MOBILE FES-CYCLING SYSTEM WITH PEDAL FORCE MEASUREMENT TO OPTIMIZE TRAINING PERFORMANCE

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Abstract: Cycling induced by Functional Electrical Stimulation (FES) is a well-established technique for the rehabilitation of neurological patients. The CYBATHLON initiative in the recent years has renovated the interest in this discipline, able to combine the advantages coming from the sport practice with the typical therapeutical benefits of FES. In this work, a novel system for outdoor FES-cycling is proposed. The system integrates a passive recumbent trike, two four-channel stimulators (one for each leg) and sensorized pedals for the real-time recording of the tangential and radial forces that the pilot is exerting over the pedals with each leg independently. One healthy subject was involved in a testing session during which different pedalling conditions were evaluated. Results evidenced the possibility of using the force information to identify cases of unbalanced cycling. Furthermore, these measurements could be exploited to validate and optimize the stimulation strategy and to overall analyse and improve training performance.

Keywords: FES-cycling, sensorized pedals, tangential force, stimulation strategy, CYBATHLON

Introduction

Damages to the Central Nervous System, such as Spinal Cord Injury (SCI) and stroke, cause lifelong disabling conditions including a partial or total loss of sensations and motor functions. Affected individuals also develop highly impairing secondary health issues due to immobility (e.g. venous thrombosis, osteoporosis, pressure sores) [1]. Functional Electrical Stimulation (FES) is a commonly used therapeutic option in such cases, promoting recovery of motor functions and reducing secondary symptoms [2]. This technique, investigated since the 1960s, induces artificial muscle contractions by delivering low-level electrical pulses via superficial electrodes placed over the muscle belly. Proved therapeutical benefits of FES, along with a partial or total recovery of functional movements, include augmented cardiorespiratory fitness, promotion of blood circulation and greater muscle volume, increase of strength, endurance and mass of paralyzed muscles [3], decrease of bone mineral loss [4] and increase of range of joint motion [5].

Increasing interest is growing around the combination of FES with sport activities, which adds psychological advantages to the aforementioned therapeutical benefits of FES, favouring social inclusion and more engaging rehabilitative sessions. FES-cycling is a leading example of "Sport Therapy", which allows both indoor and outdoor

practice, raising the idea that it might become a recreational activity for people with disabilities. In recent years, it has gained a renovated interest thanks to the CYBATHLON initiative [6], which includes FES bike among its disciplines. However, some limitations are still related to this exercise because of its low metabolic efficacy (the ratio between external work output and metabolic energy input) and early fatigue onset [7] compared to volitional cycling. These are due to the non-physiological muscle recruitment induced by FES, mainly caused by the synchronous triggering of muscle fibres and the preferential activation of type II fast-twitch muscle fibres [8]. Thus, the maximization of efficacy and minimization of muscle fatigue are central challenges in the FES-cycling research field, especially considering non-ideal scenarios, such as rough or sloping surfaces. To this aim, an optimization of the FES control strategy is needed. In FES-cycling, muscles groups of the lower limbs are stimulated sequentially [9], trying to emulate their physiological activation patterns. The stimulation strategy is defined by means of a look-up table specifying the range of the crank angle in which each muscle has to be stimulated to generate the movement. In addition to the ranges, spatial and temporal characteristics of the stimulation waveform can be manipulated as well, by adjusting different parameters (i.e., current amplitude, pulse width, and frequency). These parameters, together with the stimulation ranges, affect the resulting cycling performances. Thus, to optimize the FES control strategy care must be devoted to the development of measures used to monitor in real-time cycling performance.

The aim of this study is to present a mobile FES-cycling system adapted for people with disabilities. The system consists of a commercial recumbent trike instrumented with an encoder for the measurement of the crank angle and sensorized pedals for recording the radial and tangential forces transmitted to the crank by the subject. A preliminary analysis of the tangential force signals acquired on one healthy subject showed the possibility to quantify in real-time eventual pedalling unbalances and to validate the stimulation strategy used to induce the pedalling movement. These measurements will allow to evaluate and optimize the training performance.

Methods

Subject

One single healthy subject (male, 25 years, 1.78 m, 65 kg) participated in this case study. The Ethical Committee of Politecnico di Milano approved the study in September

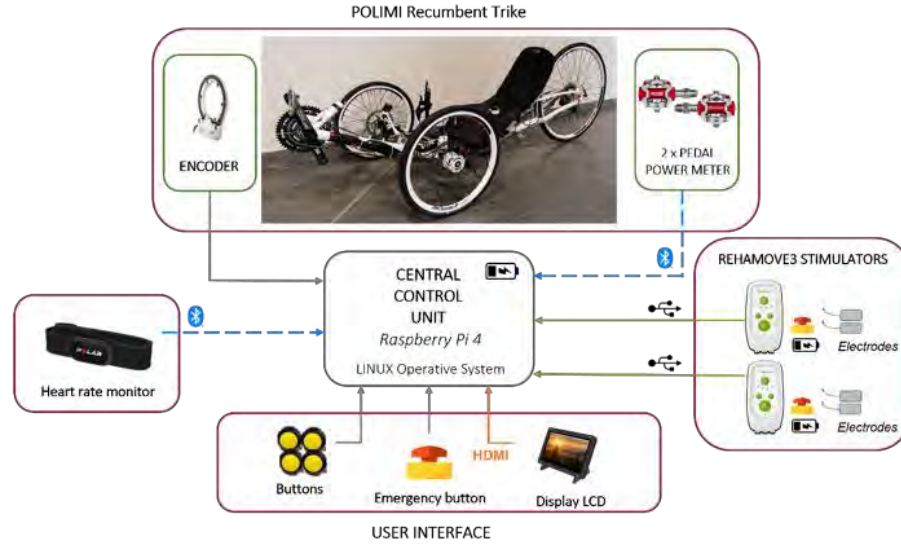


Figure 1: Experimental set-up.

2019 and the recruited subject provided his written informed consent.

Experimental setup

A scheme of the FES-cycling system is shown in Fig. 1. A commercial recumbent trike (ICE VTXTM, 2017) has been adapted to be used by subjects with limited mobility. A magnetic absolute encoder (AksIMTM, RLS) measures the crank angle with a sample frequency of 200 Hz and a resolution of 16 bits (0.0055°). Two commercial MTB/quick release pedals (X-Power, SRM GmbH) allow measuring the radial and tangential forces exerted by both legs on the pedals (sample frequency 30 Hz). Cycling shoes with pedals-compatible cleats are used; in case the pilot is a disabled subject, custom-made ankle foot orthoses (AFO) are added to keep the ankle angle at 90° and the movement of the legs constraint to the sagittal plane. For each leg, a current-controlled stimulator (RehaMove3TM, Hasomed GmbH) with four channels and surface self-adhesive electrodes (Pals® from Axelgaard Manufacturing Co. Ltd.) are used to deliver rectangular biphasic pulses, completely balanced in terms of charge. The interface between the user and the system consists of 4 buttons plus an emergency one. This latter controls the feeding of every component and, when pushed, cuts the current flow putting the system in a safe state condition. Additionally, a 5 inches touch screen display allows the user to modify the initial settings of the program and visualize useful data about stimulation (current intensity, pulse width and frequency), training session (elapsed time, measured force and actual pedalling cadence) and system state (pedals and stimulators residual battery charge). Finally, a heart rate sensor (H10 thoracic band by Polar) is included in the system to monitor the status of the subject. The heart rate and the R-R intervals are sent to the central control unit with a frequency of 1 Hz. The control unit of the system consists of a Raspberry Pi 4 model B with a Raspbian operating system – a Linux based Distribution. The OS kernel is modified with a real-time patch pre-empt-RT 4.19 to ensure that processes scheduling uncertainties and consequent unpredictable response

latencies are managed efficiently. The Raspberry Pi 4 provides many communication interfaces and protocols which allow the connection of the board with the devices mounted on the trike. General Purpose Input Output (GPIO) pins are used both for the connection of the encoder through Serial Peripheral Interface (SPI) and for the interface with the physical buttons. Two USB ports are used to connect the stimulators (only for data communication as stimulators are powered by their own battery). A micro-HDMI port is used for the connection with the display. The Bluetooth Low Energy (BLE) protocol is used for the communication with the wireless devices, i.e. the force sensor pedals and the heart rate sensor. The system is fed by a power bank and all the electronic components are enclosed in a 3D printed box mounted on the back of the seat such that the trike can be used in outdoor environments.

FES Control Strategy

The control software running on the Raspberry Pi controls the two multichannel stimulators.

For each leg, four muscle groups are stimulated: quadriceps, gluteal muscles, hamstrings and gastrocnemius. The pedals position is used to sequentially activate the muscle groups during each cycle, in such a way that each one is contracted during a specific angular range.

The muscle stimulation ranges are obtained by means of a biomechanical model of FES-induced pedalling developed in MATLAB/Simulink® (The MathWorks, Inc. USA) starting from the work of Riener et al. [10]. Within the simulation environment, muscle groups are individually stimulated for a series of complete revolutions. Then, the angular ranges in which each of them gives an active contribute to the pedalling movement are computed as the difference between the force exerted during the stimulation phase and the one obtained during passive cycling, i.e. when the movement is driven by an external motor, following a procedure described in [11].

The current amplitude delivered to each muscle is modulated by a Proportional Integrative (PI) control, in order to maintain a pre-determined reference pedalling cadence,

while the stimulation frequency and the pulse width are kept constant at 40 Hz and 400 μ s, respectively.

The PI performs the same action for all muscle groups, while initial values of current amplitude as well as saturation values are defined individually for each muscle. During program execution, the subject could interact with the system through physical buttons to activate various functionalities: to switch on/off the stimulation, to enable/disable the PI control action and to increase/decrease the current amplitude.

Experimental protocol and data analysis

The experimental trials were conducted during the same day under identical conditions. The trike was used indoor, placed over a smart trainer (Wahoo Kickr, Wahoo FitnessTM) considering a 5% resistance value and the lowest gear ratio. Cadence was kept constant at 30 RPM and the duration of each trial was about 1 minute. The first trial consisted in a voluntary pedalling test without FES (Voluntary), during which the subject was asked to perform a symmetrical exercise with the two legs. Then, other two trials without FES were performed and the subject was required to exert a higher force with one of the two legs (first with the right (Test 1) and then with the left one (Test 2). Finally, in the last trial, the subject was asked not to voluntarily participate to the movement and FES was delivered to induce the cycling movement (Test 3).

The tangential forces were recorded for each trial. Mean values and standard deviations were calculated over a series of revolutions. The RMSE (Root Mean Squared Error) between the force profiles of the symmetrical voluntary pedalling trial and those of the FES-induced trial was computed in order to verify the ability of the system to replicate the voluntary movement.

Results

The tangential force profiles were extracted and plotted with respect to the crank angle in order to compare and analyse the different conditions.

Fig. 2 shows the comparison of tangential force profiles between the three voluntary cycling trials. Panel A compares the symmetrical pedalling trial with the one in which an unbalance in favour of the right leg is simulated: it can be noticed that the tangential force of the right pedal (in red) exhibited a higher positive peak and a lower negative peak with respect to the symmetrical test (in grey). During the same trial, the tangential force of the left pedal shows the opposite behaviour. In panel B, the symmetrical pedalling trial is visually compared with the left-leg predominant trial and the behaviour of the right and left force profiles is exactly the opposite.

Fig. 3 shows the comparison of the tangential force profiles between the symmetrical voluntary pedalling trial (in grey) and the FES-induced cycling trial, while the stimulation strategy identified with the biomechanical model is reported in Fig. 4. Please consider that the zero angle corresponds to the position with the right foot up in the vertical axis. Focusing on the comparison between the voluntary symmetrical cycling trial with the FES-induced one, it can be stated that this latter one displays a slightly different

shape profile, a more irregular trend and a phase displacement with respect to the voluntary profiles.

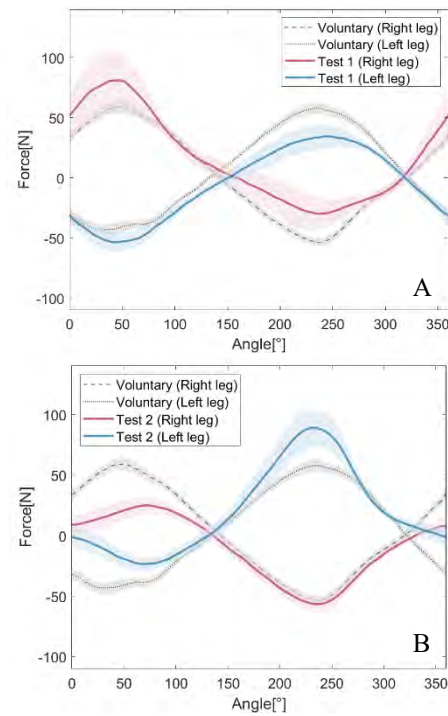


Figure 2: Tangential force profiles of the three voluntary cycling condition: the symmetrical trial is reported in grey in both panels; the right-leg predominant trial is reported in panel A, while the left-leg predominant trial is shown in panel B. In the picture, the mean and the standard deviation calculated over the cycles of each single trial are plotted.

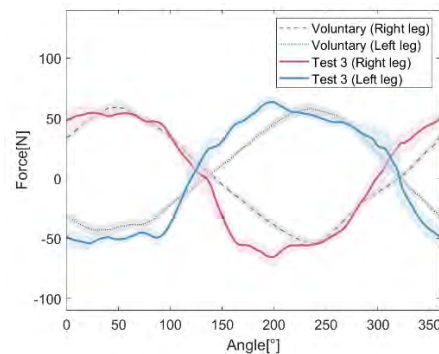


Figure 3: Tangential force profiles of the voluntary symmetrical trial (in grey) and the FES-induced pedalling trial. In the picture, the mean and the standard deviation calculated over the cycles of each single trial are plotted.

Compared to the maximum mean force peaks of the voluntary condition, data from the FES-induced cycling trial show a wider positive force profile during the pushing phase mainly induced by the stimulation of the Quadriceps, and a wider negative force profile during the pooling phase, induced by the stimulation of Hamstrings and Gastrocnemius. The RMSE between the force profiles of the voluntary symmetrical trial and the ones of the FES-induced trial, normalized with respect to the peak-to-peak amplitude of the voluntary trial, was 0.13 and 0.15, for the left and right leg respectively. Overall, the FES-induced force profile can be considered to have an almost symmetrical behaviour between the two legs.

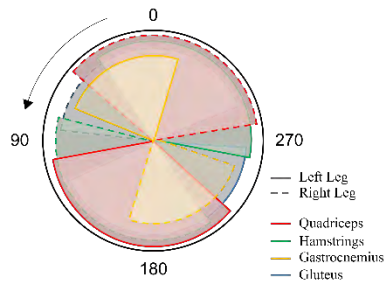


Figure 4: The set of stimulation angular ranges.

Discussion

This study presents a novel mobile FES-cycling system which includes the possibility to measure in real-time the tangential and radial forces exerted by each leg independently at the pedals. In order to evaluate the potentiality of this system, tangential force profiles with respect to the crank angle were measured under different experimental conditions in one healthy subject.

The first comparison (Fig. 2) allows us to appreciate the difference between the force exerted by each leg since pedals give independent measures. Consequently, the here proposed system is able to identify a situation where unbalanced forces are applied while pedalling. Considering this, it would be possible to implement personalized stimulation strategies based on the specific characteristics of each pilot and also to differently modulate the stimulation amplitude between the two legs in order to assure a symmetrical pedalling. This consideration is particularly interesting in cases of lower limb asymmetry, such as in stroke survivors. In the second comparison (Fig. 3), some differences in the force profiles shape and timing can be highlighted between FES-induced and voluntary cycling. In particular, the former one displays a wider shape and a phase shift for both legs. However, RMSE values and force amplitude were comparable between the two trials, considering both legs and both peaks (minimum and maximum). This proves that the identified stimulation ranges are suitable for a physiological-like pedalling, which is a prerequisite to delay the fatigue onset and prolong the exercise as much as possible. To conclude, this case study showed the potentialities coming from the addition of force measurements at the pedals of a mobile FES-cycling system. Similarly to what has been previously observed by our group for FES-cycling stationary system [12,13], force measurements at each pedal can be exploited to optimize the stimulation strategy, to modulate the stimulation amplitude during training in order to assure a symmetrical pedalling movement and to monitor the training performance over time. The future aim will be to exploit this information in order to optimize cycling efficiency and postpone the onset of muscle fatigue in people with disabilities. Customized AFO will be used in combination with the pedals to keep the legs constraint in the sagittal plane.

Acknowledgement

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EFFECTS OF STIMULATING TRUNK AND HIP MUSCLES ON REACH AND ARM STRENGTH AFTER SPINAL CORD INJURY

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Abstract: This pilot study explores the effect of three electrical stimulation (ES) conditions, namely 'ES Trunk', 'ES Trunk Hip Extensors', and 'ES Trunk Hip Extensors and Flexor', on seated bimanual reach and arm strength in 6 individuals with cervical spinal cord injury (SCI). ES was provided by a full-body suit with built-in surface electrode pairs. Bimanual reach was assessed with maximum anterior center of pressure excursion (COPE) and tube displacement. Arm strength was determined by isokinetic push and pull peak force and average power on a dynamometer. Results showed no significant differences between ES conditions and 'no stimulation' at group level, but individual results showed that most participants performed better with at least one ES condition. Bimanual reach distance and COPE increased on average by $18.9 \pm 9.0\%$ and $16.0 \pm 17.3\%$, respectively. Arm strength improved in almost all participants and their subjective experiences of ES were very positive. A conclusion is that a personalized tailored approach and further research is needed, as the optimal ES condition differed among participants and tasks.

Keywords: Trunk stability, Bimanual reach, Spinal cord injury, Electrical stimulation, Rehabilitation

Introduction

Individuals with paralysis of the trunk and hip muscles after spinal cord injury (SCI) experience impaired sensorimotor control of the spine and pelvis, leading to trunk instability, impaired trunk function, and compromised upper limb workspace.⁽¹⁾ They experience a loss of functional abilities and independence during activities of daily living⁽²⁻⁴⁾ and are exposed to a higher risk of falls.^(5,6) For these reasons, individuals with SCI consistently identify trunk stability as one of the most desirable functions to improve and as an important determinant of quality of life.⁽⁷⁾

One method of creating trunk stability is by applying electrical stimulation (ES) to the paralyzed trunk muscles. Previous studies showed that co-contraction of trunk muscles using ES increased trunk stiffness during sitting balance in able-bodied individuals.^(8,9) Moreover, a stiffer torso provides a more stable base of support for the upper extremities to work against, thereby increasing the efficiency of wheelchair propulsion and reach distance in individuals with SCI.^(1,10-12) Additionally, activating both trunk and hip extensor muscles can increase posterior pelvic tilt, concomitantly the base of the support, postural

stability, and improve the ability to restore upright sitting from forward-bent positions.^(1,13,14)

Previous research on the effects of ES to the trunk and/or hip extensors in individuals with SCI has shown improved seated posture (reduction kyphosis), interface pressure, static stability, bimanual workspace, manual wheelchair propulsion efficiency, and pulling force.^(1,13-15) In these studies, ES was only applied to one specific combination of a muscle group(s), i.e. trunk extensors,^(1,16) trunk flexor and extensor,^(11,12) or trunk extensor and hip extensors.^(10,13-15,17) To date, no studies have been conducted on the effects of simultaneously stimulating both the trunk and hip flexor and extensor muscles on bimanual reaching and arm strength or have compared different ES conditions with different combinations of stimulated muscle groups.

Therefore, the purpose of this exploratory study was to determine the effects of three ES conditions, i.e. 'ES Trunk', 'ES Trunk Hip Extensors', and 'ES Trunk Hip Extensors and Flexor', on seated bimanual reach and arm strength in individuals with cervical SCI. It was hypothesized that ES of the trunk muscles allows the arms to produce more force during push and pull movements. Additional stimulation of hip extensors would facilitate forward reach, active pull force and power. Finally, ES of trunk and hip extensors and flexor muscles would create co-contraction and thereby increases trunk and pelvis stiffness, potentially further increasing bimanual reach and arm strength.

Methods

Participants: 6 individuals with a cervical SCI (Table 1).

Table 1: Participant's characteristics

Participant No.	Sex	Age (y)	Injury Level	ASIA Grade	Time post-injury (y)
1	M	53	C3	C	32
2	M	49	C6	B	20
3	M	36	C4 - C5	C	2.5
4	M	35	C6	B	18
5	M	40	C4 - C5	C	1.5
6	M	40	C7	A	15

Study Design: Seated reach and upper-extremity force and power were assessed with two tests at Reade rehabilitation center in Amsterdam. Each test was performed twice for four conditions, whereby different combinations of muscle groups were stimulated simultaneously (Fig. 1). The ES conditions were I) No - ES; II) ES Abdominals + Back; III) ES Abdominals + Back + Hip-Extensors; IV) ES

Abdominals + Back + Hip-Extensors-Flexor. The highest values per ES condition were used to assess changes in reach and arm strength between the four conditions.

Electrical Stimulation: ES was provided by a full-body suit with built-in surface electrode pairs (Teslasuit, VR Electronics Ltd, London, UK). The muscles were stimulated bilaterally with a continuous protocol with biphasic pulses (40 Hz, ± 50 mA). The intensity of ES was individually regulated with pulse duration (100-180 μ s) to achieve the strongest tetanic contractions without strong discomfort or signs of autonomic dysreflexia, whereby the participant adopts an upright seating posture.

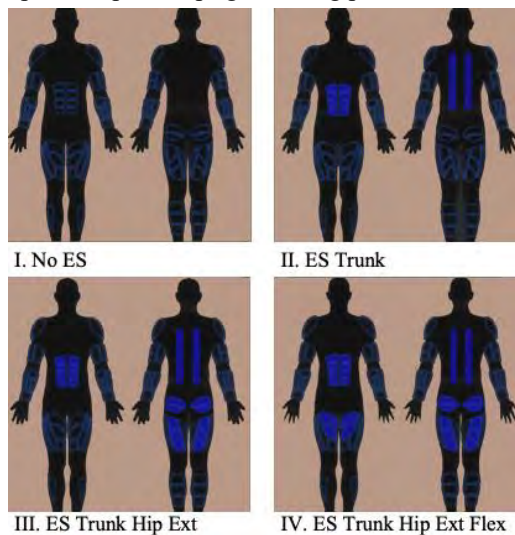


Figure 1: Electrode placement in the 4 conditions. Blue areas were stimulated per condition.

Seated bimanual reach: Participants sat on a pressure mat (BodiTrak Pro, Vista Medical, Canada) on a backless exam table. Reflective markers were placed on the right acromion, wrist, and C7. The participants bimanually held a lightweight stick with which they had to push a tube as far forward as possible and return to the upright starting position (Fig. 2). The height of the tube was set to the maximum height at which the participant could raise both (extended) arms. Only the trials in which the participant returned to the start position were analyzed. Videos of each trial were recorded with the Clinical Motion Analysis Xsystem (Cmax, Pro Care, Neth.) and shoulder anteflexion angle, C7- and wrist-trajectory were analyzed with Kinovea (v0.9.15). Displacement of the tube was measured with a tape attached to the tube. Center of pressure (COP) data were collected at 52Hz and filtered (2nd order Butterworth, 5Hz low-pass) and maximal anterior COP excursion (COPE) was calculated.

Arm Strength Test (Peak Force and Average Power): Peak force and average power during a push and pull movement with the right arm were measured with an isokinetic dynamometer (Biodex System 3 Pro™ Biodex Medical Systems, New York) and a closed-chain linear-motion at a speed of 0.061m/s. (Fig. 3). Participants pushed the attachment away from their chest and then pulled it back until starting position during two familiarization repetitions and a maximal push and pull movement. Peak force (N) was the highest value in each attempt. Average power (W) was calculated over a 3.5-s period.

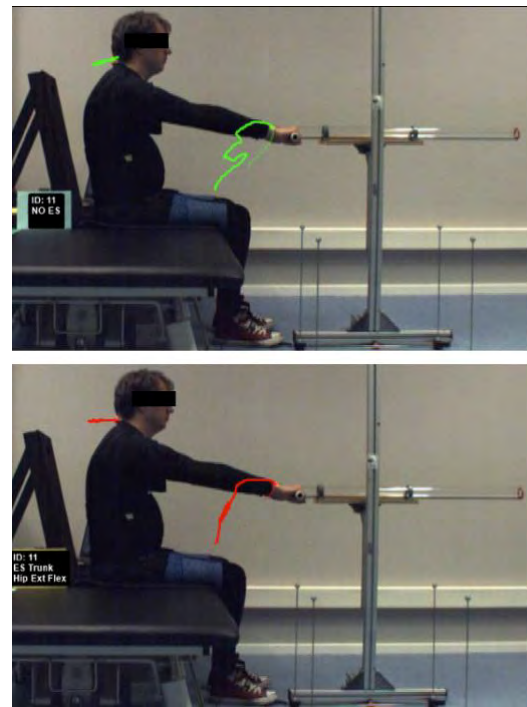


Figure 2: Maximal anterior position during bimanual reach. Top: NO ES; Bottom: ES Trunk Hip Extensors and -Flexor. Green and red lines show wrist- and C7-trajectory during reach.



Figure 3: Push and pull movement on Biodex.

Statistical Analysis: One-way repeated measures ANOVA was performed for each outcome measure. Post hoc testing with Bonferroni correction was performed for pairwise comparison of ES conditions. The level of statistical significance was set at 0.05.

Results

The preliminary results for seated bimanual reach and arm strength are summarized in table 2, figure 4, and 5.

Seated bimanual reach: Not all participants were able to extend both arms forwards during unsupported sitting and reaching. Therefore, tube height and shoulder anteflexion ranged between 72.5 - 100 cm and 35 - 68°, respectively. No significant differences between ES conditions and 'no stimulation' were found for both COPE ($p = .43$) and tube displacement ($p = .91$). However, 5 of 6 participants increased their COPE and could reach farther with ES compared to 'no stimulation'. The increase in COPE was $16.0 \pm 17.3\%$ (0.23 ± 0.24 cm), while tube displacement increased by $18.9 \pm 9.0\%$ (3.38 ± 1.34 cm). ES enabled different reach strategies, e.g., participants 1, 3, 4, and 6 could extend their elbows 2 – 45° more, and participants 2, 3, and 6

Table 2: Results bimanual reach and arm strength.

	No - ES		ES Trunk		ES Trunk Hip Ext		ES Trunk Hip Ext Flex		F	p
	Mean	SD	Mean	SD	Mean	SD	Mean	SD		
COPE (cm)	3.38	3.13	2.71	2.64	2.67	2.79	2.73	2.76	0.97	.43
Displacement tube (cm)	17.5	8.3	17.8	8.3	17.7	6.3	16.8	7.7	0.18	.91
Peak Force Push (N)	186.0	86.8	190.1	78.8	189.5	74.2	194.6	82.1	1.33	.30
Peak Force Pull (N)	131.7	38.7	132.9	48.8	129.9	47.2	128.6	38.8	0.94	.45
Average Push Power (W)	9.4	4.7	9.7	4.2	9.6	4.1	9.7	4.2	0.01	1.00
Average Pull Power (W)	6.4	2.0	6.5	2.5	6.4	2.4	6.4	1.9	0.53	.67

COPE, center of pressure excursion; SD, standard deviation; Ext, extensors; Flex, flexor.

were able to increase their trunk excursion by 3 – 5° while reaching. Large inter- and intra-individual differences in reaching distance and COPE were observed, and participants achieved their best results during different ES conditions. In addition, ES conditions had a different effect on COPE and tube displacement for 4 participants (Fig. 4). **Arm strength:** All participants achieved higher peak forces during the isokinetic pushing movement with at least one of the three ES-conditions compared with ‘no stimulation’. Large intra-individual differences were found, and participants benefited from different ES conditions. The effect of ES was greatest for the condition in which both the trunk and hip extensor muscles were stimulated, 2 participants improved peak push force by 15.3 and 17.6% (18 and 22N), respectively. ES of trunk and hip extensors and flexor resulted in higher peak push forces in the 4 other participants, improvements ranged

from 1.9 – 8.4% (3 – 19N) compared to ‘no stimulation’. However, these differences were not significant at group level ($p = .30$). The effect of the ES conditions on peak force during isokinetic pulling differed among participants. ES increased peak pulling force in 4 participants. Trunk ES resulted in 4.8 and 10.5% (8.1 and 16.3N) higher peak pull force in 2 participants, while ES of both trunk and hip extensors increased peak pull force by 3.1 and 7.8% (3.7 and 17.7N) for 2 others. Overall, no significant differences were found for peak pull force ($p = .45$) and for average push and pull power ($p = 1.00$ and $p = .67$) between the ES conditions and ‘no stimulation’.

Discussion

Results of this exploratory study on the effects of different ES conditions on bimanual reaching and arm strength after cervical SCI indicate the potential of ES and demonstrate

Bimanual Reach

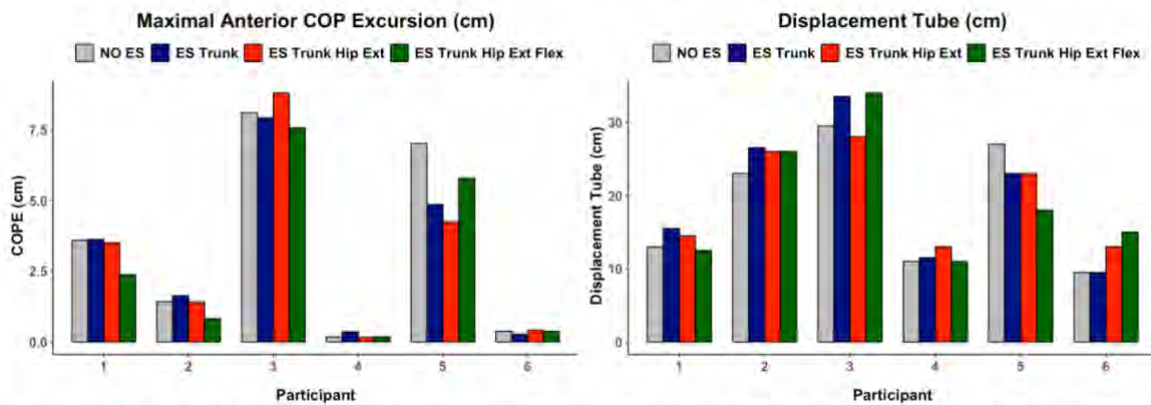


Figure 4: Bimanual reach, maximal values per condition and participant. Left: Maximal anterior COP excursion. Right: Tube displacement.

Isokinetic Peak Force (N)

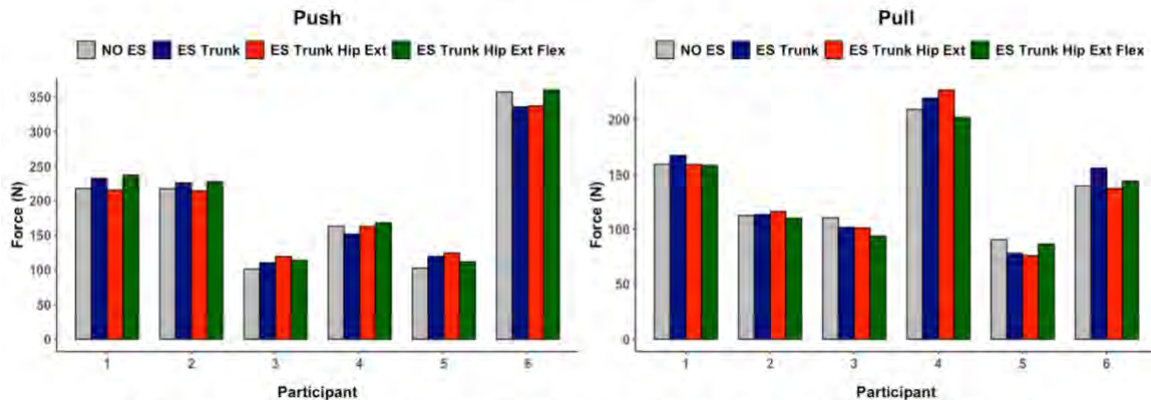


Figure 5: Maximal isokinetic peak force per condition and participant. Left: Peak push force. Right: Peak pull force.

the importance of a tailored personalized approach. Almost all participants improved bimanual reach and arm strength with at least one of the three ES conditions compared to 'no stimulation'. Responses to the different ES conditions were highly variable among participants benefiting from different ES conditions. Moreover, no optimal ES condition was found per participant.

Previous studies showed that co-contraction of trunk muscles using ES increased trunk stiffness during sitting balance in able-bodied individuals.^(8,9) In addition, a stiffer torso provided a more stable base of support for the upper extremities to work against.⁽¹⁰⁻¹²⁾ It is not clear if this mechanism also applied to this study since ES was applied to both lumbar and thoracic part of m. Erector Spinae and stimulation intensity of the lower back was too weak to induce tetanic contractions. Nevertheless, individual results showed that 4 of 6 participants increased reach and arm strength with 'ES Trunk' compared to 'no stimulation'.

Results of the condition 'ES Trunk Hip Ext' were variable among participants which was in line with the results of Triolo *et al.* (2013).⁽¹³⁾ This was the first study to investigate if ES of hip flexors, in addition to trunk and hip extensors, could improve arm strength and bimanual reach. The condition 'ES Trunk Hip Ext Flex' has potential because most participants preferred this condition and some participants performed better than 'without stimulation' or even achieved their best results in this condition. Video analysis showed that participants could use different strategies to achieve the upright sitting posture before reaching and while reaching. For example, less posterior pelvic tilt, less backwards (and even forwards) displacement of C7, and longer reach duration. Moreover, the pathway of the wrist and C7 were much smoother with 'ES Trunk Hip Ext Flex' compared to 'no stimulation' (Fig. 2). Largest improvements were seen in participants with a motor complete SCI.

Participants' subjective experiences were very positive. They felt more stable and liked the sensation of feeling something in their body. Participants with an incomplete SCI mentioned that ES made them feel how to move their muscles and would like to use ES as training tool. However, ES to the hip flexor causes stretch spasm in participant 5, which hindered him in generating force and reaching. This highlights the need for an individually tailored approach. Teslasuit provides an easy way to test the effect of stimulating different muscle configurations and manipulate the stimulation characteristics to achieve the optimal individual settings. This provides opportunities for further research, as the results show that the optimal ES condition differs not only among participants, but also among tasks and outcome measures. An advantage of Teslasuit is that all electrodes are built into the garment, eliminating the need for surface electrodes with attachments and wires or implanted electrodes, which were used in most previous studies, and which required surgery.^(1,13-15,17)

Limitations

Limitations include the small sample size and participant heterogeneity, compromising statistical power and

exploration of inter-individual differences and interactions with injury level and completeness of SCI. In addition, only one combination of stimulation parameters was assessed in this study, where the ES intensity was regulated with pulse duration that was relatively short (100-180 μ s) and did not induce tetanic contractions in all participants. A different combination of stimulation parameters might lead to different results. A major limitation of this study was the lack of proper lower-back stimulation since this was not possible in the current version of Teslasuit. Moreover, electrode placement was not optimal because we were using a medium size Teslasuit, and some participants' waist circumference was too large to fit the suit perfectly. Straps were used to solve this problem. The cross-sectional design of this study may have limited performance during the different ES conditions, as participants had little or no experience with ES and may need more time to learn how to use ES to improve reach, push and pull performance. Additionally, it cannot be ruled out that a learning effect occurred during the tests.

Further research

Longitudinal studies, with individual approaches stimulating different muscle group configurations with different stimulation characteristics during consecutive sessions, will provide insight into the possible effect of ES on reach and strength.

Conclusion

Results of this exploratory study indicated potential to improve bimanual reach and arm strength using ES, however, did not reach statistical significance. The responses to the ES conditions were highly variable between the participants and ES configuration needs to be personalized to achieve optimal results. Moreover, since there is a lot of difference in the effect of the ES condition, it also means that if a person wants to apply ES in daily life, he should be able to adjust the settings to achieve the best results.

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FES, Critical Care and COVID 19

Keynote - Jarvis JC¹, Swain I²

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Abstract: *in this keynote session we will have a set of linked presentations and discussion: The Covid 19 pandemic has brought the reality of mass critical care into the public eye. In particular, the high material and personal cost to patients, societies and carers of assisted breathing has been obvious. Mechanical ventilation is associated with acquired weakness in the muscles of breathing and locomotion. We will discuss the role of FES to maintain muscle during Critical Care and in the following rehabilitation phase. What are the advantages and disadvantages of the various strategies for diaphragm pacing?*

Keywords: *mechanical ventilation, diaphragm, muscle wasting, rehabilitation, critical care*

Introduction

The use of electrical stimulation to activate the muscles involved in breathing has a 70 year history and the idea goes back at least to the late 18th century. Implanted systems are established for patients with high cervical injury and who require near continuous assisted breathing. In the context of short term support of breathing, however, where recovery in a number of days or weeks is anticipated, fully-implanted systems are not warranted, and there are various possible approaches to stimulate muscles to assist the work of breathing, and to prevent further decline. Several groups have investigated the use of abdominal muscle activation to assist weaning from the ventilator and the use of lower limb stimulation that may reduce wasting and reduction of perfusion and we have published a recent survey of this area with colleagues [5].

In this session we will hear from representatives of teams working on transcutaneous, intravascular and percutaneous phrenic nerve stimulation to activate the diaphragm during mechanical ventilation. When the work of breathing is provided by a mechanical system, the diaphragm loses mass quickly. Therefore, when the medical crisis that triggered the instigation of ventilation subsides, the return to independent breathing is hindered by weakness in the primary breathing muscle.

Methods

There is good evidence that a relatively small amount of muscle activation can prevent atrophy and several experimental studies have addressed this question.

Dow et al [6] made a series of experiments in denervated rabbit extensor digitorum longus. When stimulation started at the time of denervation, then muscle mass could be preserved. Contractions were delivered across the whole 24 hours. Between 500 and 1200 contractions per day was best to preserve mass, and between 200 and 800 contractions per day to preserve force. Ashley et al [7] investigated the rabbit tibialis anterior muscle after denervation and a period of atrophy. They stimulated the muscle directly using between 600 and 6000 contractions per day and concluded - *"A surprising, and in many ways reassuring, finding from this study is that the physiological and morphological consequences of stimulating denervated muscles did not vary despite a wide difference in the patterns employed: the least demanding pattern used in this study (Pattern 1) was as effective as ones delivering up to 20-fold more impulses. It may be that the level of stimulation needed to restore muscle mass is relatively low, at least in denervated muscles that are not undergoing degeneration..... Patients (and carers) are likely to appreciate, and comply more readily with, a protocol that makes fewer demands on their time."*

Kern et al [8] used home based stimulation for rehabilitation of muscle in the elderly. Their protocol, which counteracted muscle decline, used stimulation 3 times a week, with 225 contractions per day in 3 x 10 minute sessions. And, for healthy persons, the recommendation from the American College of Sports Medicine for hypertrophy training is 2-3 days per week for novice and intermediate training and 4-5 days per week for advanced training.

These findings suggest that the signal for muscle maintenance lasts for many hours, so that activation for a short time once per day or intermittently across the day is effective. Indeed, resistance exercise causes an enhanced sensitivity to the stimulatory effect on

protein synthesis of amino acids for at least one day in humans [9, 10]

All interventions to activate the diaphragm via the phrenic nerve must include a stimulation system. Thus, electrode placement or choice from an array, stimulation current, pulse width, frequency, burst pattern, active and rest periods, all need to be decided upon. The interaction, if any, with the ventilator system must be established. For example, whether activation of the diaphragm should be adjusted to place it in the same phase of the respiratory cycle when tidal volume or respiratory rate are adjusted. It must be decided whether data from the ventilator system will be

Results

As we said in a recent narrative review, “*The rehabilitation of patients with COVID-19 after prolonged treatment in the intensive care unit is often complex and challenging. Patients may develop a myriad of long-term multiorgan impairments, affecting the respiratory, cardiac, neurological, digestive and musculoskeletal systems. Skeletal muscle dysfunction of respiratory and limb muscles, commonly referred to as intensive care unit acquired weakness, occurs in approximately 40% of all patients admitted to intensive care. The impact on mobility and return to activities of daily living is severe. Furthermore, many patients experience ongoing symptoms of fatigue, weakness and shortness of breath, in what is being described as long COVID [1, 2]*”.

In the first 7 months of 2020, there were more than 10,000 COVID-19 admissions to critical care in the UK National Health Service (NHS), about 4 times greater than historic annual cases of viral pneumonia (3). Critically unwell patients generally require a longer course of respiratory support, exacerbating other risk factors for acquired weakness after critical care (3) which is seen in 20–50% of patients with COVID-19 admitted to critical care (4)”.

The presentations in this session will describe pre-clinical, and some early clinical data on diaphragm activation to give an overview of the potential of these various systems to reduce the material and human cost of critical care.

Discussion

The session will include live discussion of some of these aspects, including presubmitted or live questions from the conference delegates.

used to control the stimulation or to monitor progression or decline of breathing function, and whether diaphragm assist will be applied in both prone and supine positions. Furthermore, it must be decided how often supervision by specialist staff will be required, to bring stimulation equipment into the critical care setting, to apply electrodes, and to adjust stimulation parameters. To what extent can this disruption be minimised? Can systems be designed that integrate easily with the existing critical care infrastructure and that can be operated by the specialist nursing staff?

Acknowledgement

This abstract owes much to the work done for the narrative review - Effect of neuromuscular electrical stimulation on the recovery of people with COVID-19 admitted to the intensive care unit: A narrative review. Burgess LC, Venugopalan L, Badger J, Street T, Alon G, Jarvis JC, Wainwright TW, Everington T, Taylor P, Swain ID. *J Rehabil Med*. 2021 Mar 18;53(3):jrm00164. doi: 10.2340/16501977-2805.PMID: 33634830

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Spatially Distributed Sequential Stimulation Improves Fatigue Resistance in Functional Electrical Stimulation Rowing

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Abstract: A critical limitation of functional electrical stimulation (FES) for rehabilitation exercises is the rapid onset of muscle fatigue. Here we investigated spatially distributed sequential stimulation (SDSS) for improving fatigue resistance in FES-rowing exercise in 15 able-bodied (AB) participants (five female) where participants rowed with voluntary arm effort while minimizing voluntary leg muscle contraction. Fatigue was characterized by the total trial length and time elapsed until a 20% decrease in power output occurred (TTF). Trial length was significantly longer in SDSS rowing (paired *t*-test, $p < 0.01$, $d = 0.71$), with an average SDSS:SES trial length ratio of 1.31 ± 0.47 . TTF_{SDSS} was significantly longer than TTF_{SES} (Wilcoxon signed-rank, $p < 0.01$, $r = 0.62$) with a median SDSS:SES ratio of 1.34 ranging from 1.03 to 5.41. SDSS improved fatigue resistance in FES-rowing where trial length was longer by 31% and participants maintained high rowing power output for 34% longer in a clinically relevant exercise for individuals with spinal cord injuries.

Keywords: Asynchronous stimulation, electrical stimulation therapy, exercise therapy, muscle fatigue, functional electrical stimulation (FES), rowing

Introduction

Physical activity is an important aspect of health especially for those with spinal cord injury (SCI). Individuals with SCI often lead a sedentary lifestyle due to limb paralysis that contributes to many secondary medical conditions [1]. Functional electrical stimulation (FES) exercises can be used in rehabilitation programs to improve cardiovascular health in individuals with SCI, however, acute muscle fatigue is a major limitation in FES applications [2]. Possible causes of fatigue in conventional electrical stimulation, which we call single electrode stimulation (SES), include activating only a local subset of motor units and stimulation is usually much higher than natural frequencies [3].

We proposed spatially distributed sequential stimulation (SDSS) as a method to reduce this rapid muscle fatigue by distributing the stimulation sequentially and spatially via multiple electrodes [4]–[8]. In SDSS, multiple electrodes are placed on a stimulation site and lower frequency stimulation pulses are sent one after another sequentially “rotating” across the electrodes. Previous studies have shown that SDSS is effective at improving fatigue resistance in isometric tasks in lower limb muscles for both able-bodied (AB) individuals and individuals with SCI [4]–[8]. However, few studies show the effect of SDSS on muscle

fatigue in a dynamic exercise context such as hybrid FES-rowing exercise where voluntary rowing action of the upper limbs are coordinated with FES of lower limb muscles. Thus, the purpose of this study was to investigate the effect of SDSS on muscle fatigue in FES-rowing in able-bodied participants.

Methods

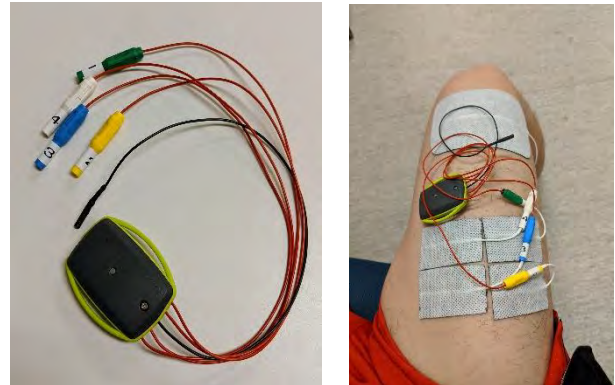


Figure 1: Proprietary in-line adapter (left) for spatially distributed sequential stimulation attached to electrode array over quadriceps (right)

Fifteen able-bodied (AB) individuals with no history of neurological disorders (aged 24.8 ± 3.2 years, five females) participated in this study (Tab. 1). Each participant gave informed written consent to the experimental procedure. This study was approved by the Research Ethics Board of the University Health Network in accordance with the Declaration of Helsinki on the use of human subjects in experiments.

A programmable 4 channel neuromuscular electrical stimulator (Compex Motion, Compex SA, Switzerland) delivered FES to the quadriceps and hamstring through self-adhesive gel electrodes (ValuTrove, Axelgaard Manufacturing Co. Ltd., USA). SDSS stimulation was delivered via a custom-made proprietary adapter in-line with the stimulator and electrodes (Fig. 1). Electrical stimulation was delivered manually by the participant with a push button on the handle. The stimulation waveform parameters were a biphasic asymmetric pulse with pulse duration of 450 μ s. The stimulation frequency was 40 Hz for SES and was split into 4 phase-shifted 10 Hz pulses to each electrode for SDSS (Fig. 2).

Table 1: Participant Demographics

Participant	Age	Height (cm)	Weight (kg)	Sex	FES Naïve
1	25	185	70	M	N
2	24	178	72	M	N
3	24	152	57	F	N
4	25	178	65	M	N
5	35	187	79	M	Y
6	23	152	43	F	Y
7	24	152	57	F	Y
8	22	180	64	M	N
9	27	172	75	M	Y
10	25	187	90	M	Y
11	25	174	80	M	N
12	22	165	61	F	Y
13	20	172	79	M	Y
14	27	162	66	M	Y
15	24	158	53	F	N
Mean	24.8	170.3	67.4	F=5	Y=8
SD	3.2	12.2	11.9		

A commercially available rowing ergometer (Concept2 model D, Concept2 Inc., Morrisville, Vermont, USA) was modified with custom-made back and leg rests for FES-rowing. The ergometer was instrumented with 5 load cells (GS1240-250 and SML-300, Interface Advanced Force Measurement, Durham Instruments, Arizona, USA) and 2 linear string potentiometers (Measurement Specialties, Durham Instruments, Arizona, USA) to measure rowing force and rower position, respectively. One load cell was connected in series with the rowing handle, the other four load cells were mounted under the left and right foot plate. String potentiometers were connected to the back of the seat and the handle.

The exercise protocol consisted of FES-rowing performed across two sessions separated by at least 48 hours. Maximum tolerable stimulation was determined by increasing FES intensity in 1 mA increments until maximum tolerable intensity was identified. The stimulation intensity used for the rowing trials was 80% of maximum and was matched across SES and SDSS sessions. The participant rowed at a self-selected arm rowing intensity and FES driven leg contraction at 80% of maximal stimulation intensity (Fatiguing Rowing). There were three endpoints for Fatiguing Rowing: voluntary exhaustion, leg collapse, or pain. Voluntary exhaustion occurred when the participant felt too tired to continue rowing but were still able to complete the rowing motion. Leg collapse occurred when legs could no longer support the rowing motion despite continuous FES. Pain as an endpoint occurred when the stimulation was causing too much discomfort or pain to continue rowing. The participant was encouraged to maintain a steady stroke rate and was asked to avoid voluntarily contracting leg muscles throughout the fatiguing trial. The order of SES and SDSS rowing sessions was counterbalanced.

Fatigue was defined by total trial length and time to fatigue

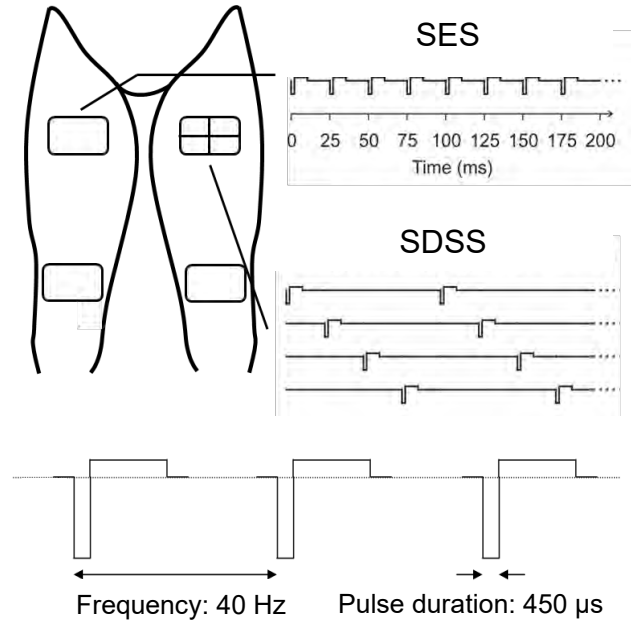


Figure 2: Stimulation parameters used for single electrode stimulation (SES) and spatially distribute sequential stimulation (SDSS)

(TTF) of Fatiguing Rowing. The trial length was defined as the time elapsed until one of three endpoints was reached during Fatiguing Rowing (i.e., voluntary exhaustion, leg collapse, or pain). TTF was defined as the time elapsed until a 20% drop in power output from initial power output occurred. Peak power per stroke was extracted and filtered by a 30-point moving average filter to produce power output. To ensure that only steady state rowing was included for analysis, the first 5 strokes were excluded, and the initial power output was defined as the average peak power of the subsequent 10 strokes. For these measures, data normality was tested using the Shapiro-Wilk test. Wilcoxon signed-rank tests were performed for non-normally distributed data and two-tailed paired t-tests were performed for normally distributed data. Significance and effect size of non-parametric tests were described by p - and r -values, respectively. Significance and effect size for parametric tests were described by p - and d -values, respectively. A p -value less than 0.05 ($p < 0.05$) indicated statistical significance.

Results

Tab. 2 shows the trial length and the endpoint for each participant. Trial length for SDSS was significantly longer than SES (28.8 ± 15.9 minutes SDSS, 22.6 ± 11.4 minutes SES, $p < 0.01$, $d = 0.71$). The ratio of SDSS to SES rowing trial length across all participants was significantly larger than 1.00 at 1.31 ± 0.47 ($p < 0.01$, $d = 0.70$). Voluntary exhaustion was the endpoint for 7 participants. Leg collapse was the endpoint for 6 participants. One participant stopped the SDSS trial due to pain; another participant stopped both trials due to pain.

Table 2: Total Trial Length

Participant	Trial Length (min)			Reason for Stopping	
	SES	SDSS	SDSS:SES	SES	SDSS
1	13.6	15.8	1.16	Leg collapse	Leg collapse
2	14.2	13.1	0.92	Leg collapse	Leg collapse
3	5.0	8.5	1.71	Leg collapse	Leg collapse
4	27.2	38.1	1.40	Voluntary	Voluntary
5	15.3	12.5	0.81	Voluntary	Voluntary
6	28.2	37.1	1.32	Leg collapse	Leg collapse
7	17.9	27.9	1.56	Leg collapse	Leg collapse
8	31.8	32.5	1.02	Leg collapse	Pain
9	15.3	22.6	1.48	Voluntary	Voluntary
10	30.7	42.5	1.40	Voluntary	Voluntary
11	50.0	75.3	1.51	Voluntary	Voluntary
12	20.8	18.7	0.93	Pain	Pain
13	36.7	34.6	0.94	Voluntary	Voluntary
14	24.4	27.8	1.14	Voluntary	Voluntary
15	8.8	24.7	2.79	Leg collapse	Leg collapse
Mean	22.6	28.8	1.31		
SD	11.4	15.9	0.47		

Fig. 3 shows a representative time course of filtered power output for SES and SDSS rowing of one participant where the total trial length (indicated by the length of traces) of SDSS rowing was longer than SES. Furthermore, the time at which SDSS power output crossed the fatigue threshold was longer than that of SES, resulting in a longer TTF for SDSS rowing. Fig. 4 shows group TTF results with median TTF of 10.6 and 17.9 minutes for SES and SDSS,

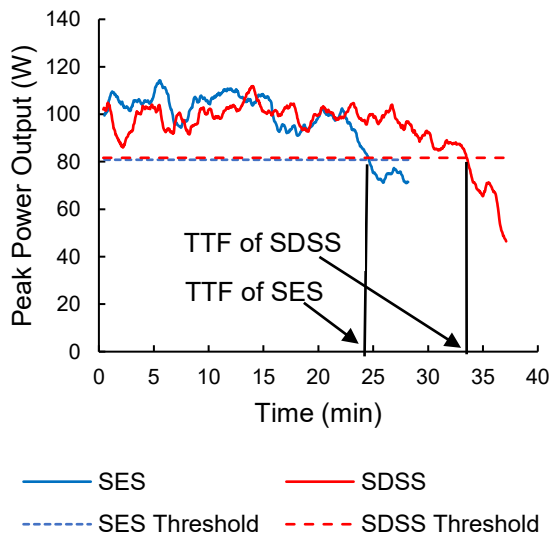


Figure 3: A representative time course of filtered peak power output that shows for both single electrode stimulation (SES) and spatially distributed sequential stimulation (SDSS) fatiguing rowing. Fatigue thresholds of SES and SDSS rowing were set at 80% of the initial power output. Initial power output was determined as the average power output of the first 10 strokes.

respectively. TTF_{SDSS} was significantly longer than TTF_{SES} ($p < 0.01$, $r = 0.62$) (Fig. 4a). The ratio of TTF_{SDSS} to TTF_{SES} had a median of 1.34, ranging from 1.03 to 5.41 (Fig. 4b). Despite the large variation, no participant experienced a decrease in TTF with SDSS rowing (i.e., a ratio less than 1.0).

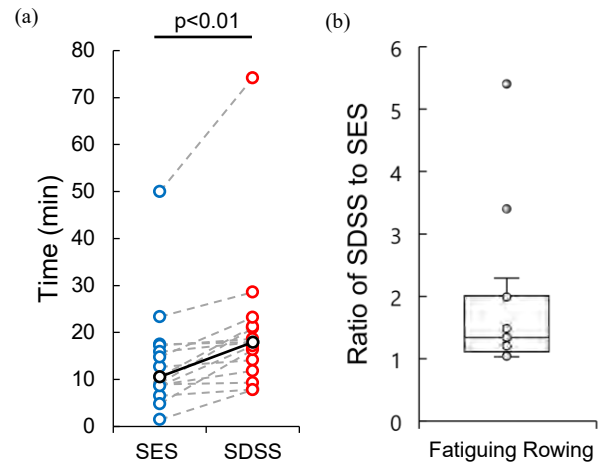


Figure 4: Time to fatigue (TTF) of single electrode stimulation (SES) rowing and spatially distributed sequential stimulation (SDSS) rowing. (a) Time in minutes of TTF_{SDSS} and TTF_{SES} , with median in black. Statistical significance was calculated with a Wilcoxon Signed Rank Test. (b) Box and whisker plot of ratio of TTF_{SDSS} to TTF_{SES} , the box contains the 25th and 75th percentile with the center line denoting the median. Whiskers extend above and below the box to data elements that are not outliers. Outliers are data points more than or equal to 1.5 times the interquartile range.

Discussion

Fatiguing Rowing trial length was significantly longer in SDSS rowing by approximately 31%, i.e., SDSS trial lengths were 1.31 ± 0.47 times longer than SES. The large deviation seen in the group data could be explained by 4 participants experiencing a 5.7% to 18.6% shorter trial length with SDSS whereas the other 10 participants experienced a 2% to 279% increase. Although participants were verbally encouraged throughout the trial to continue rowing until leg collapse, trial length was dependent on individual endurance. The subjective nature of trial length was why we also measured TTF as a quantitative measure of performance.

A median ratio of TTF_{SDSS} to TTF_{SES} of 1.34 suggests that SDSS increased fatigue resistance by about 34%. Furthermore, despite the large variation in TTF, no rower experienced a decrease in TTF when using SDSS. Fatigue resistance from SDSS is well documented in isometric and isokinetic tasks with a large range in performance improvement with SDSS [4]–[9]. As far as we are aware, this study is the first to report improved fatigue resistance with SDSS in FES-rowing, and the second in a dynamic FES exercise context [10]. SDSS significantly improved fatigue resistance, in similar amounts as single joint studies, in a dynamic FES-exercise context meaningful for SCI rehabilitation. Our results suggest that SDSS should be able to extend FES exercise times by 31% percent and maintain a high power output for 34% longer in clinical settings.

Our results were from AB participants who mimicked FES-rowing in individuals with SCI by relaxing their legs during stimulation. We planned to include individuals with SCI but were not able to do so due to COVID-19 restrictions. This AB model of SCI may not completely mimic FES-rowing in individuals with SCI as AB participants might have unknowingly exerted voluntary force. However, even if the participants exerted some voluntary force exertion, this AB model may approximate performance in individuals with incomplete SCI where we expect some voluntary contribution. While the results were promising, further investigation, especially with individuals with SCI, is required.

Acknowledgement

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C-Cuff electrodes: an updated durable 3D SLA printed cuff electrode

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Abstract: 3D stereolithography (SLA) offers a means to rapidly produce durable custom cuff electrode shells with high spatial resolution and reproducibility. Maintenance of electrical isolation, especially at the closures and hinges of the cuff, and assembly/packaging with contacts and lead-out wires to form functional electrode structures for small (<1.5mm dia.) nerve bundles with contact dimensional factors < 1mm remained a challenge. This paper describes the development of a new cuff electrode with carbon contacts and closure system that enables rapid production of functional devices. The new devices consist of the C-cuff with I-beam closure and carbon graphite contacts. Prototype devices were implemented and tested in-vivo for surgical handling and implantability on the sciatic nerve of anaesthetized Sprague Dawley rats. They were used to deliver pulse stimulation, effect low frequency alternating current (LFAC) block, and record compound action potentials. Device functional performances were comparable or better than those for traditional metal contact cuff electrodes.

Keywords: cuff electrode, 3D printing, rapid prototyping

Introduction

In 2018 we introduced a novel 3D stereolithography (SLA) printing approach for rapidly prototyped and tested stainless steel cuff electrodes with non-standard geometries [1]. High resolution 3D SLA printing was the first step in providing a highly reproducible technique and offered a fine-detailed electrode shell with less time and equipment required than previous approaches. Our current research aim, involving the effect of electrode geometry on low frequency alternating current (LFAC) [2], [3] motivated the need for a robust cuff electrode that could be customized and fabricated with little down time and high fidelity. Exploring the broad range of nonstandard test variables in spatial contact changes as well as scalability in inner diameter required a nonstandard approach. LFAC, with its demanding low frequency electrode charge capacity requirements demanded an electrode with low, low frequency impedance to stay within the water window. Previous approaches to cuff electrode designs, primarily silicone-based methods, require more time and specialized equipment to create the same level of precision offered with 3D printed cuffs [4]–[9].

The hinge design (Fig. 1A) contributed to an initial robust 3D printed cuff but was outweighed by significant functional design flaws and limitations. Limited inner diameter, current leakage at the hinge and opening, and multiple contacts for each measurement point were among the most prominent design concerns.

A new U-cuff design (Fig. 1B) was created to address issues with current leakage at the hinge and the discontinuous contacts. The U-cuff featured a single component shell with a vertical opening and inset windows on the back surface. Removal of the hinge supported continuous stainless steel contact plates that reduced the number of wires needed per cuff, moderately improved the circumferential contact coverage, and improved upon some of the current leakage. The uninsulated opening the width of the nerve diameter, without the use of a structural closure, was still susceptible to current leakage and required a mineral oil bath to provide insulation. The windows on the back side of the cuff were intended to direct glue away from the surface of the contacts to prevent fouling and assisted in contact. Unfortunately, the windows did not offer the desired amount of support or protection during the assembly process.

Design changes from the hinge cuff to the U-cuff still required further optimization. A robust 3D printed cuff design needed to overcome a lack of structural insulation, contact surface area, and contact stability. A new C-cuff model (Fig. 1C) has been implemented to further address limitations seen in both the hinge and U-cuff models. This design is a scalable, durable, and stable structure that offers complete circumferential insulation through the combination of a cuff shell and a novel I-beam closure.

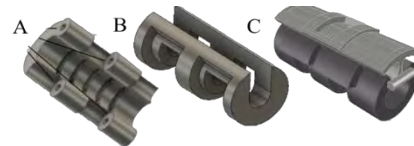


Figure 1: 3D printed cuff design evolution from A) hinge cuff to B) U-Cuff to C) C-Cuff with I-beam closure.

Methods

3D Printed Design: The cuff and closure base designs and modifications are modeled in a CAD software (AutoCAD 2022) for implantation optimization and experimental aim. All cuff shells are C-shaped cylinders that covers approximately 80 percent of the nerve circumference. Insets on the back side of the cuff create windows to precisely define the contact surface and wire locations, as well as prevent contact-to-contact shunting. Window covers are added into the design at the ends of the windows on the backside of the cuff assist with wire placement during the assembly process. This base design is capable of scaling inner diameter (ID), contact number, contact width, contact pitch, and contact edge-to-end distance to optimize cuff geometries for our research aims. The closure spans the length of the cuff, with a stopper at one end to prevent slide-through during implantation. This

component covers the remaining open surface of the nerve at the opening of the cuff to provide complete insulation.

3D Printing: 3D cuff and I-beam designs are exported from the CAD software as STL files and imported into the 3D printer software (Preform 3.2.2, Formlabs Inc). Cuffs were printed on a SLA 3D printer (Form 2, Formlabs Inc.) using clear photopolymer resin (FLGPCL04, Formlabs Inc.) and rinsed in isopropyl alcohol upon print completion. Parts were cured in a heated UV cure chamber (Form Cure, Formlabs Inc.).

Surgical Implantation and Testing: After contact placement and assembly, cuffs were implanted *in vivo* to validate the spatial fit in the region of interest with the target nerve. The *in vivo* impedance of C-cuff structures is tested before and after experimentation to ensure safety and validate the robustness of the structure. After successful implantation, data is collected to test the ability of the structure to record peripheral nerve compound action potentials. A recruitment curve is also collected to test the cuff's ability to stimulate peripheral nerve activity in acute studies.

Results

Design: These cuffs have been successfully printed with varying geometries and contact numbers. The smallest inner diameter we have successfully attempted is 500 μm . The I-beam closure functions as intended to secure the cuff around the nerve and provide total structural insulation around the nerve.

Surgical: These devices have reproducibly and successfully been implanted on the tibial nerve of rats in acute experiments. The I-beam closure fits precisely within the cuff opening to offer a physical barrier that keeps the nerve in place without additional sutures. Compared to previous hinge closures, this design further improves upon the time needed for implantation with less cable management and moving structure to work with.

Electrical Functionality: The *in vivo* impedance of this device is within safe and stable functional ranges, changing minimally before and after experiments (Fig. 2A). The C-cuff electrodes were able to repeatedly record (Fig. 3A) and stimulate (Fig. 3B) acute neural activity on the target nerve.

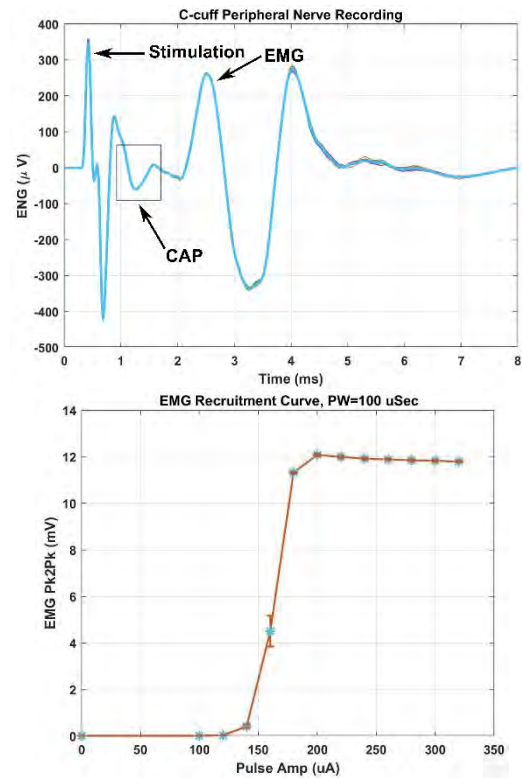


Figure 3: A) ENG showing cuff recordings of the compound action potential and B) a recruitment curve showing successful cuff stimulation based on EMG recordings.

Discussion

The new C-cuff design has improved upon all major design limitations seen in both the hinge and U-cuff models. The resultant cuff is a more stable, robust, and electrically favorable device compatible with our desired research aims that require these customizable, non-standard dimensions and designs. The use of CAD software and 3D printing has made it possible to make these rapid modifications and improvements to the designs of both cuff and closure as needed. These structures are limited to acute studies, but once the geometries of the cuff are fixed, movement toward a more biocompatible, chronic solution is desired.

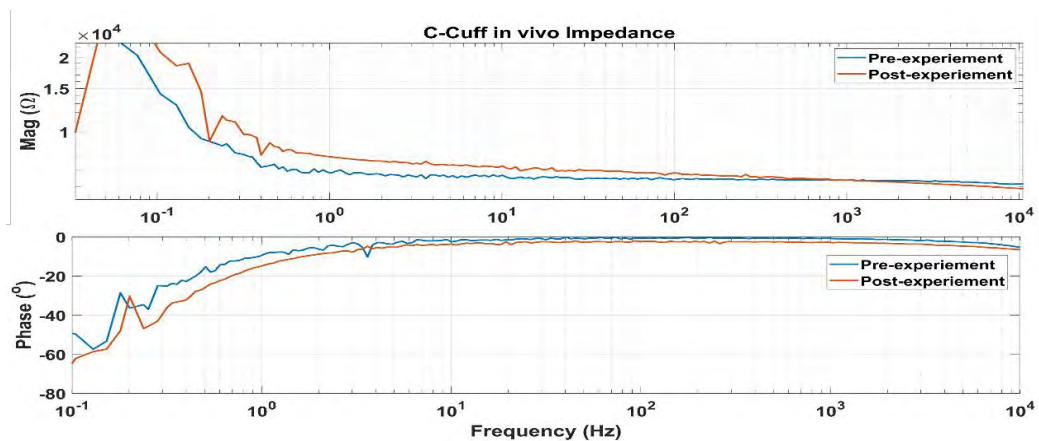


Figure 2: Pre- and Post experiment Bode plot demonstrates the impedance magnitude and phase are within favorable ranges.

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Novel High Performance Poly(3,4-ethylenedioxythiophene):Polystyrene Sulfonate (PEDOT:PSS) + Carbon-black Based Bioelectric Interface

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Abstract: *The stimulation and recording performance of implanted neural interfaces are often limited by the electrode contact impedance characteristics when the electrode structure is implanted in neural tissue. A novel intrinsically conductive polymer (ICP) was developed that markedly improves the electrode contact charge storage capacity (CSC) and contact impedance. The ICP was electrodeposited onto a carbon graphite electrode contact. The increased CSC reduces what would otherwise be a high-potential environment that could lead to non-linear charge transfer especially at low frequencies (10 Hz). This, allowed for a safer and more effective means to pass low frequency alternating currents (LFAC) as well as increased recording stability. Contacts with an area of $2.1 \times 10^{-2} \text{ cm}^2$, showed an average charge storage increased of a factor of 30. Their corresponding impedance at 1 Hz was slightly above 1 k Ω , a 99.99% decrease compared to the uncoated state.*

Keywords: *Intrinsically Conductive Polymer, Neural Electrodes, Charge Storage Capacity, Electrode Contact*

Introduction

Neuromodulation is the process through which electrical current is used to promote an ionic current that alters the ionic environment in proximity to the nerve. This change in the local environment may lead to a physiological response such as initiation and propagation of an action potential within the nerve. Electrical current may be delivered in various forms, the most notable include pulses, bursts, high-frequency alternating current (HFAC), and the recently developed low-frequency alternating current (LFAC) [1][2][3]. Irrespective of the application, electrodes must be designed to safely provide therapeutic stimulation whereby electrical current effectively transverses across the electrode-electrolyte boundary where it is converted into ionic current.

At low frequencies (<10 Hz), the capacitive reactance tends to be large as a result of its inverse relationship with frequency. Capacitive reactance makes it difficult to effectively store charge in the electrode-electrolyte interface and leads to high impedance and poor bridging of the electrical to ionic current in media. Ultimately this leads to poor recording and a potentially dangerous environment at the electrode-electrolyte interface during neurostimulation. In the early days of neuromodulation, electrode structures consisted of a bare metal needle, also known as a conventional metal electrode (CME). Although good at conducting current at high frequencies (>100Hz), CMEs

have drawbacks such as inability to mediate the electrode-electrolyte interface across all forms of electrical stimulation, a result of their inherent polarizability, and a high probability of eliciting an immune response that leads to an increase in local impedance [4] [5]. The CME drawbacks can be diminished through careful selection of metals that are less polarizable, such as Pt or Iridium-Oxide, by use of ICPs, or some combination thereof. In the past decade, research has shown that a low polarizable metal-ICP complex is currently the favorable approach to mediating the interface. In the present, a novel ICP electrode has been developed to improve the charge transfer characteristics across a broader range of frequencies, which a focus of improving functionality in the low frequencies where capacitive reactance dominates.

Methods

Fabrication of the ICP Electrode Structure: A 1.3 mm ID rigid cuff electrode containing two contacts were 3d-printed [see companion conference paper, Doering et al.]. Cyanoacrylate percolated with graphite to enable conduction was deposited within the electrode wells and affixed to a stainless-steel wire, creating wired electrode contacts. A novel ICP consisting of EDOT:PSS in a CB suspension was prepared prior to its use in electrodeposition. EDOT was oxidatively electropolymerized on the CG contacts to complete the fabrication of the ICP electrode.

Electrochemical Analysis: Electrochemical Analysis consisted of electrochemical impedance spectroscopy (EIS) and cyclic voltammetry (CV) with a sweep-rate (SR) of 4000 mV/s. Recordings were made at two separate points, once before and after the electrodeposition using an electrochemical interface (SI1287, Solartron). EIS and CV were performed in phosphate buffer saline solution at pH 7.4 in both cases and an additional CV was performed after deposition with a SR of 50 mV/s. Cathodic charge storage capacity was calculated using custom written software in MATLAB (Matlab 2020b, The Mathworks).

Results

The percolated carbon graphite contacts prior to coating had a cathodic CSC of -22.11 mC and -47.52 mC which was increased to -805.3 mC and -1108 mC following ICP deposition (SR = 4000 mV/s). Impedance at 1 Hz prior to deposition was $2.636 \times 10^6 \Omega$ (-33.64° phase) and $3.075 \times 10^5 \Omega$ (-62.92° phase) which was decreased to 1448 Ω (-11.59° phase) and 1463 Ω (-16.80° phase) following ICP deposition (Figure 1). In both cases, the impedance

appeared to reach R_{∞} at low frequencies (< 10 Hz). The additional CV performed after electrodeposition (SR = 50 mV/s) had a cathodic CSC of $-623.6 \text{ mC}\cdot\text{cm}^{-2}$.

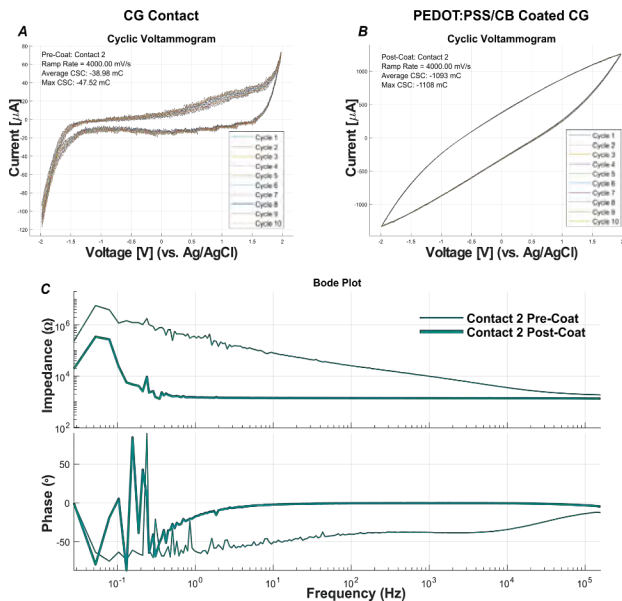


Figure 1: Cyclic voltammogram and the corresponding electrochemical impedance spectrogram of the carbongraphite contact before and after PEDOT:PSS/CB coating.

Discussion

The properties of the carbon graphite contact are similar to CME showing an impedance where reactance becomes dominant below 1kHz, and resistive at frequencies $> \sim 1\text{kHz}$. As such, sourcing current for waveforms that are predominantly composed of high frequencies, such as traditional rectangular pulse stimulation, is generally possible within the linear region of the electrode. However, any bias currents or DC offset current is magnified by the high low frequency impedance. This can lead to offset instabilities during recordings, or electrode polarization during

stimulation. It is particularly problematic when attempting to use CMEs to effect Low Frequency Alternating Current block or DC block.

The results show that the novel CB + PEDOT:PSS ICP could be effective at allowing for improved charge transfer in low-frequencies. The impedance at 10 Hz remained predominantly resistive in character and consistent with the impedances at high frequencies ($> 1\text{kHz}$). These results indicate that the coating may be effective across all frequencies required during neuromodulation as well as many other various forms of current delivery and use of the electrodes to record nerve activity.

Acknowledgements

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Strain Analysis in Spinal Cord Surrogate to Investigate the Mechanical Stability of a Novel Wireless Intraspinal Microstimulation Interface

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Abstract:

We report on a novel wireless intraspinal microstimulation (ISMS) interface that aims to restore standing and walking in individuals with spinal cord injury. Current and emerging ISMS implant designs connect the electrodes to the stimulator through lead wires that cross the dura mater. To reduce possible complications associated with transdural leads such as tethering and leakage of cerebrospinal fluid, we aim to develop a wireless, fully intradural ISMS implant based upon our prior work in the cortex with the Wireless Floating Microelectrode Array (WFMA). Although we have extensive data about WFMA cortical stability, their mechanical and electrical stability in the spinal cord remain unknown. In this preliminary study, a physical model of the spinal cord was studied using an electronic micromotion apparatus, simulating typical spinal cord motion. Strain fields were digitally analysed using an optical method known as digital image correlation (DIC). The results demonstrate that DIC can be used for in-vitro screening of intraspinal implants.

Keywords: Intraspinal microstimulation, Digital image correlation, Wireless array

Introduction

Following spinal cord injury, the muscles, their innervating neurons, and the segmental spinal circuitry below the level of injury remain largely intact. Therefore, rehabilitation interventions that activate the surviving neural elements have been

investigated. Intraspinal microstimulation (ISMS) has emerged as a promising neuromodulation technique for restoring standing and stepping in individuals with spinal cord injury [1].

Current ISMS implant designs consist of fine microwire electrodes placed with the tips bilaterally targeting the locomotor networks in the ventral horn of the lumbar enlargement. Experimental results to date in acute and chronic animal models have been very compelling, demonstrating long distances of overground walking as well as long-term stability of the implant and functional outcomes [2, 3]. However, current ISMS implant designs connect the electrodes to the implanted stimulator through lead wires that cross the dura mater. Spinal cord electrode wires are potentially problematical due to the chronic adverse tissue responses, tethering forces on the electrodes (with spinal cord movement) [4], and cerebrospinal fluid leakage caused by the transdural conduits.

To mitigate these potential problems, we aim to develop a wireless ISMS interface that eliminates both tethering forces on the electrodes and the transdural conduit (Fig.1.). The feasibility of this proposed system is supported by an existing 5mm-diameter wireless floating microelectrode array (WFMA) which is now in use in an FDA-approved clinical trial for intracranial occipital cortex stimulation for visual restoration for those with profound blindness (NCT04634383). Powering and communications across the dura are accomplished via magnetic coupling.

In our cortical preclinical studies, the WFMA devices provided a stable neural interface [5]. However, their mechanical and electrical stability in the spinal cord are unknown. The spinal cord moves independently from the surrounding vertebrae. It undergoes a relatively large range of deformations, when compared to cortical tissue, during typical daily activities, including compression, extension, and torsion [6]. Electrode arrays implanted in the spinal cord must therefore be mechanically compatible with the cord itself and must neither impede the natural motion of the spinal cord nor damage it during deformation.

A physical model of the spinal cord could be highly informative for the development and testing of new electrode-array-type spinal interfaces. For initial screening tests, this approach may be preferable to working with spinal cords harvested from animals, both to minimize the number of animals used in testing, and to expedite high throughput in bench and mechanical testing experiments.

One of the quantifiable metrics to assess implant stability is mechanical strain. In vitro studies have indicated that

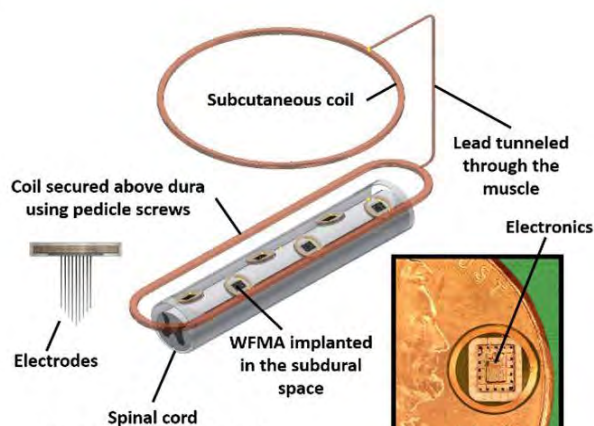


Figure 1: Wireless ISMS concept showing subdural WFMA and epidural power/communication coil

induced strain can cause activation of pro-inflammatory pathways [7]. Primary CNS glia exposed to cyclic strain upregulate a host of proinflammatory cytokines that could trigger tissue remodeling and interact with the blood-brain barrier [8]. In the study reported here, a physical model of the spinal cord tissue was developed based upon a method conceived at the University of Alberta [9]. A micromotion apparatus was constructed to simulate physiological motion within the tissue. The apparatus uses high-precision linear actuators to apply longitudinal stress on the cord sample, thus mimicking natural strain. Strain fields were digitally analysed using a non-contact optical full-field technique known as digital image correlation (DIC).

Methods

A. Micromotion apparatus

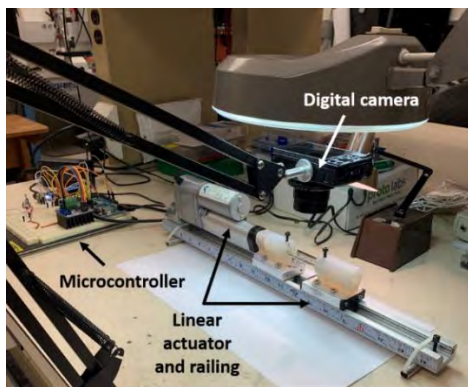


Figure 2: Experimental setup including a linear actuator and railing, a microcontroller, a digital camera mounted on an overhead tripod, and a ring light.

During daily motion, the spinal cord is subjected to a broad range of torsion, flexion, and elongation. *Margulies et al.* [10] used motion-tracking MRI to evaluate the deformation of the cervical spinal cord during neck flexion and extension and found that the maximal strain during natural motion was 12%. As depicted in Fig. 2, a feedback linear actuator (Firgelli, FA-PO-35-12-2) was used to simulate the maximum theoretical 12% total cord extension. The actuator was equipped with a built-in feedback potentiometer to determine and control its position at any point in time. The speed and motion of the linear actuator were controlled by an Arduino microcontroller. A linear slide rail (Firgelli, FA-SGR-15N-20) was used to provide accurate, stable, and smooth linear guidance. Two sliding carriages were used; one was attached to the actuator while the other was fixed in position by increasing internal friction with the rail. Two custom 3D-printed fixtures were made to allow for attachment and testing of various sizes of spinal cord surrogates. To facilitate the clamping of the cord to the stand, two screws were used to tighten the holes within the fixture. The two ends of the cord model were covered with a thin piece of plastic to prevent damage by distributing the force, due to the clamping screws, over a larger surface area.

B. Spinal cord surrogate

As described in [9], formaldehyde-crosslinked 12% gelatin surrogate cords were used to evaluate the mechanical

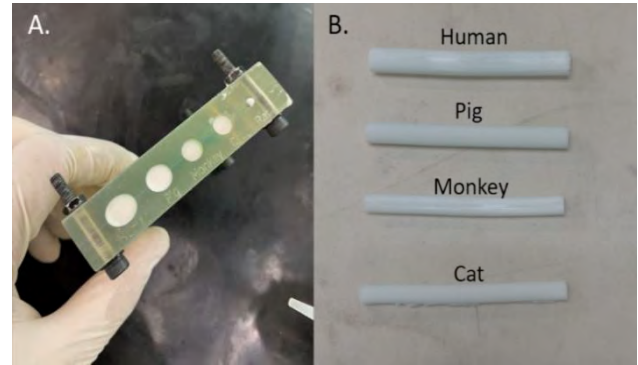


Figure 3: 3D printed mold used to fabricate spinal cord surrogate of species commonly used in research (A). Spinal cord surrogates after extraction from the mold (B). The surrogate cords feature elliptical cross section. Only the human-based sample was used in this study

interaction of electrode arrays implanted in the spinal cord. Gelatin powder was obtained from Sigma Aldrich (G1890, gelatin from porcine skin). To prepare the uncrosslinked gelatin, the powder was dissolved in distilled water. The solution was heated to 55 °C and stirred at a rate of 500 revs/min for 20 min. Formaldehyde (19.4 mmol/ 100 mL) was added and the solution was stirred for an additional 15 minutes at 45 °C. During the final 5 minutes of stirring, drops of white acrylic paint were added to the solution while stirring and until the solution was saturated and the color was evenly distributed. The solution was then poured in a custom-made mold with elliptical cross sections. The mold allowed for casting spinal cord surrogates that were 70 mm in length (50 mm to resemble the length of lumbar spinal cord in humans and an additional 10 mm at each end to clamp to the fixture). The mold, with the solution inside, was then refrigerated for 120 minutes. The mold was slowly opened, and the cord samples were carefully pulled out.

C. Strain measurement

To measure strain, the optical DIC algorithm was used to match the reference and deformed images, as provided by a speckle pattern on the cord model. As described earlier, each cord sample was colored white which served as background for the speckle pattern. To achieve increased contrast, acrylic black paint was used to apply the speckles. Each speckle was manually applied to the sample by submerging a 26-gauge blunt tip needle in acrylic black ink and using the ink adhered to the tip to paint the speckles. The speckle pattern was left to dry for 30 minutes (speckle pattern shown in Fig. 4.).

The camera (G7 X Mark II) was fixed to an overhead tripod mount to visualize the top patterned side of the surrogate cord. A few drops of DI water were added below the sample to reduce friction and to simulate the presence of cerebrospinal fluid. The micromotion testing apparatus and the camera were stabilized during the experiment to prevent motion artifacts.

The linear actuator was programmed to reach full cord extension, which amounted to 12% strain, over a period of 1 second. Therefore, a 2-second video was recorded for each trial (leaving 0.5 a second, before motion starts and after motion stops, as a buffer). The video was then trimmed, leaving only the period during which the motion occurred. The video

was then split into 50 separate frames (20 milliseconds per frame). An open-source digital image correlation engine (DICE) was used to compute full-field displacements and strains from the sequence of acquired digital images. The parameters used by the DICE software are listed in Table 1.

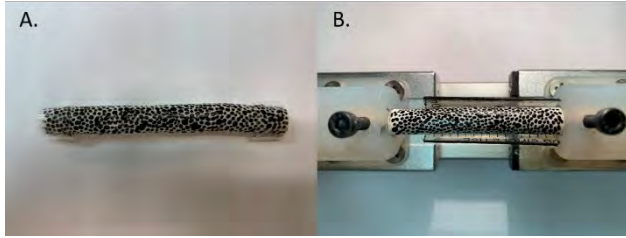


Figure 4: The speckle pattern applied to the dorsal side of the cord surrogate with a couple of thin plastic squares at each end to protect the sample from damage due to pressure from clamping screws (A). The spinal cord surrogate fixed in the micromotion mechanical testing apparatus (B).

Table 1: parameters used by the digital image correlation engine (DICE) to compute strain and displacement

Parameter	Value, Selection
Step size	11 pixels
Analysis mode	Subset-based full field
Subset size	31 pixels
Step size	11 pixels
Filtering	Gaussian filter
Filter window size	5 pixels

The region of interest was divided into subsets. The size of each subset was set to be 31 by 31 pixels. This size was selected so that each subset contained at least 3 speckles to ensure reasonable resolution and isotropy in the subset matching process. The analysis was run on the whole set of frames acquired for each sample. The first frame was used as the reference frame. Displacement and strain data were exported in matrix form. The solutions were visualized using ParaView; an open-source multi-platform data analysis and visualization application.

To examine the effect of implanting WFMA devices on the strain field, 5 WFMA devices were inserted into the spinal cord surrogate using a rapid insertion surgical device [11]. Strain data were collected, as described above, with and without WFMA devices, the latter serving as control.

Results

As shown in Fig. 5., the strain was visualized using a color map. Dimensionless strain values (in millimeter per millimeter) are indicated by the color bar.

The strain map for the control spinal cord showed an evenly distributed mechanical strain throughout the sample. The strain map of the cord in which 5 WFMA devices were implanted suggested that a higher level of mechanical strain is

present in proximity to the WFMA devices along the axis of applied stress.

Discussion

Previous studies used reference markers to study the uniformity of deformation throughout the cord model [9]. To visualize the distribution of strain within the cord under elongation, the distance between the markers was measured before and after deformation. The spatial resolution was limited by the size of the spinal cord segments between the markers. Therefore, these methods do not provide enough resolution to visualize mechanical strain in the sub-millimeter to micron scale.

DIC was selected as it allows for monitoring the displacement fields on the visible surface of a specimen, overcoming the main limitations of mechanical or optical transducers. This is a great advantage since biological soft tissue samples are neither regular in shape nor homogenous and elongate non-uniformly.

As an initial example to demonstrate the utility of DIC, strain maps in a spinal cord surrogate were generated with and without WFMA devices implanted. As one would anticipate, the strain is evenly distributed in the cord surrogate when no devices are present. When several WFMA devices are implanted, higher levels of strain appear in proximity to each device along the direction of applied stress. It is likely that the group of electrodes in each WFMA immobilize the cord surrogate beneath each array; therefore, preventing an even distribution of strain. Consequently, greater strain appears in the area surrounding each device.

While it appears that the strain may be constrained within the electrode array, it is not known whether this level of strain could result in a significant strain-induced scar tissue reaction. Nevertheless, this tool provides a means for evaluating various microelectrode arrays designs that minimize strain. Future in vivo experiments, using different types of floating microelectrode arrays, shall improve our understanding of the relationship between mechanical strain and the long-term functional stability of the implants. In the meantime, the tuneable nature of this model (adjustable direction, magnitude, and frequency) combined with accurate optical strain measurements will enable researchers to optimize implant design over a wide range of motion conditions.

The two-dimensional digital image correlation approach presented herein can only measure displacements on the surface of the material. Therefore, it does not provide displacement measurements within the three-dimensional volume. An alternative technique, known as digital volume correlation (DVC) can be used to calculate displacements throughout the volume of the cord surrogate [12]. It can, therefore, be used to examine strain along each electrode shaft. Microbeads embedded in a semi-transparent polymer can be used to provide the contrast necessary for the DVC algorithm to track mechanical deformation.

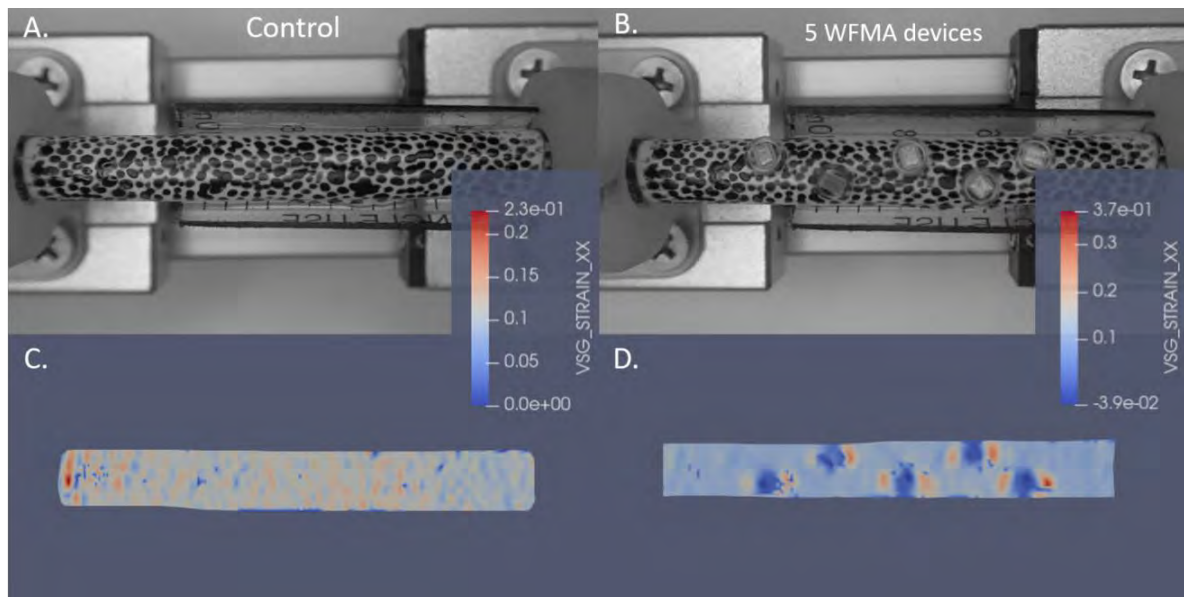


Figure 5: Spinal cord testing setup without WFMA devices (A). Spinal cord testing setup with 5 WFMA devices implanted (B). Strain field color map of spinal cord surrogate without WFMA devices (C). Strain field color map of spinal cord surrogate with 5 WFMA devices implanted (D). All images of testing setup and strain field data represent the final frame recorded at 12% strain. Dimensionless strain values, in millimeter per millimeter, are shown with color bars.

The current micromotion apparatus only allows for simulating longitudinal stress. It could be modified to allow for simulating other modes of cord motion such as bending and torsion.

Acknowledgement

The authors thank Craig Johnson, supervisor of the Illinois Institute of Technology machine shop for his assistance in machining the components of the micromotion apparatus.

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NON-INVASIVE PHRENIC NERVE STIMULATION TO AVOID VENTILATOR INDUCED DIAPHRAGM DECONDITIONING IN CRITICAL CARE: SYSTEM DESIGN AND FEASIBILITY.

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Abstract: *Diaphragmatic dysfunction has been described in the early stages in patients connected to mechanical ventilation. It is one of the main causes of weaning failure, associated with increased morbidity and mortality and high healthcare costs. A non-invasive phrenic nerve stimulator to induce diaphragm contraction was developed and tested in 10 young, healthy volunteers. We demonstrated that non-invasive phrenic nerve stimulation is feasible by surface electrodes on the neck to bilaterally activate the phrenic nerve during non-invasive ventilation in healthy volunteers. No adverse outcomes were noted.*

Keywords: *Electrical stimulation, Surface electrodes, Diaphragm dysfunction, Mechanical Ventilation.*

Introduction

Mechanical ventilation is an essential intervention in critical care medicine. However, disuse of the diaphragm during controlled-ventilation can rapidly result in severe atrophy [1]. This ventilator-induced diaphragm dysfunction (VIDD) is associated with difficulty weaning from mechanical ventilation and poor outcomes [2].

Stimulation of the phrenic nerve to induce diaphragm contraction is a promising means of maintaining diaphragm function during mechanical ventilation. Transvenous pacing has been shown to maintain diaphragm integrity in animals [3], while implanted [4] and percutaneous [5] stimulators have shown potential value in humans.

Invasive methods of phrenic nerve stimulation have several disadvantages. As well as requiring specific technical skills for implantation, limiting their widespread application, these methods carry risk during the implantation procedure as well as afterwards, and demand additional care to avoid displacement of the electrodes and infection.

Non-invasive stimulation of the phrenic nerve would offer a means to maintain diaphragm function during mechanical ventilation while avoiding the risks and technical limitations of more invasive approaches. The ability to induce diaphragm contraction using surface electrodes has been demonstrated, however these approaches rely on frames [6], collars [7,8] and hand-held probes [9] to apply pressure

to fix the electrode in position and improve coupling between the electrode and the nerve. This is not suitable for extended use in an intensive care setting, where the constant pressure risks the generation of pressure sores on the neck.

Our group therefore aimed to develop a non-invasive stimulation system suitable for maintaining diaphragm function in ventilated patients in an intensive care setting. We aimed to develop a system that reliably produces ventilator-synchronised diaphragm contraction using surface electrodes without the application of pressure.

This paper describes the work in Concepcion towards a jointly managed project between Oxford, UK and Concepcion, Chile to achieve transcutaneous activation of the phrenic nerve. The work in UK is presented in a second submitted paper. In the accompanying paper, we investigated the feasibility of non-invasive stimulation of the phrenic nerves to induce therapeutic diaphragm contraction using a concentric surface electrode. We demonstrated that non-invasive capture of the phrenic nerve is possible and characterise the parameters required to achieve meaningful diaphragm contraction in healthy volunteers.

This paper demonstrates the potential for achieving non-invasive diaphragm activation using a system suitable for use in an intensive care setting; this has the potential to reduce ventilation times, the risks associated with prolonged ventilation, and the need for highly trained clinical specialists, potentially improving clinical outcomes.

Methods

Healthy volunteers, all adults with no respiratory or neuromuscular disorders, were recruited. Written informed consent was obtained from all subjects. The study was approved by the Ethics Committee at the Universidad de Concepción, Chile (CEBB 714 – 2020).



Figure 1: Concentric ring electrode placed on the neck. The cathode is the central electrode, and the anode is the ring electrode.

Stimulation system.

A bespoke non-invasive electrical phrenic nerve stimulator was developed. The system comprises three parts: 1) Stimulator, 2) Monitoring, and 3) User interface. The stimulator was designed to produce a constant current monophasic waveform in two independent channels. Each channel can deliver current amplitudes from 1 mA to 150 mA into a 2 kOhm load with 1 mA step, frequencies from 1 Hz to 30 Hz with 1 Hz step, and pulse widths from 10 us to 400 us with 10 us step. The monitoring system is able to measure diaphragm electromyography (EMG), mechanomyography (MMG), and airway flow and pressure signals. These parameters are used to evaluate the subject's stimulation-response. Finally, the user interface was implemented on a touch screen, capable of modifying stimulation parameters and monitoring variables in real-time.

Intervention.

To perform the tests, all volunteers were asked to lie on a clinical table. After that, vital signals (blood pressure, heart rate, respiration rate, oxygen saturation) were measured at the beginning, during, and end of the intervention. Next, monitoring electrodes (EMG, MMG), flow and pressure sensors were placed. A calibration process was necessary to find the motor point and define the proper stimulation electrode placement. In this process, a probe electrode (motor point pen) was used. As the probe electrode moved over the neck, typically posterior to the sternocleidomastoid muscle at the level of the cricoid cartilage, the current amplitude was modified until diaphragmatic activation was detected. The activation was corroborated by ultrasound to

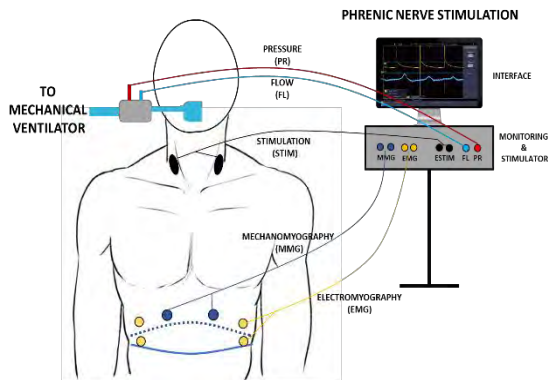


Figure 2: Phrenic Nerve Stimulator System setup. EMG electrodes placed at the intersection point of the sixth and eighth intercostal space. MMG sensors were placed just next to the EMG electrodes.

detect diaphragm movement, and through the monitoring sensors. Once the motor point was found, the stimulation electrodes were positioned. For this research, we explored a concentric ring electrode (Figure 1). These bespoke electrodes were made by modifying commercial electrodes (Axelgaard® Ultrastim); a 10 mm diameter was made for cathode and 40 mm and 30 mm external and internal diameter for the ring anode, respectively.

Finally, volunteers were connected to a non-invasive mechanical ventilator (NIV). The ventilator (Flight Medical Innovation Ltd, model Flight 60) was configured in assistive mode, and the ventilatory parameters were defined according to the volunteer's normal breathing rate.

All volunteers were ventilated and electrically stimulated for 10 minutes. Figure 2 diagram the system set up and electrodes and sensors positioning on the volunteer.

Results

10 healthy volunteers were evaluated, 5 male and 5 female. The mean (range) age was 31(26-39) years, the mean weight was 76.9 (66.1-94.6) kg., and mean BMI was 26.9 (22.9-36.6). Bilateral phrenic nerve stimulation was possible in all participants. Stimulation and ventilation were synchronised successfully. Vital signs measured during remain between physiological range, no significant changes were registered. 4 subjects reported discomfort during stimulation, mainly pricking sensations due lack in skin electrode adhesion. No other adverse effects were reported. Table 1 shows stimulation parameters used during functional testing with the mechanical ventilator for each volunteer. The frequency values to sustained diaphragmatic contractions were achieved with frequencies between 11 Hz to 15 Hz. Concerning the current amplitude values, the

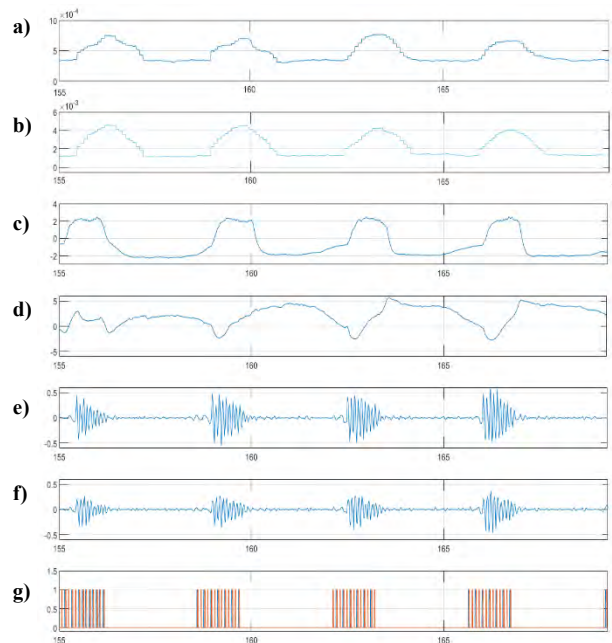


Figure 3: Phrenic nerve stimulation during NIV. Traces represents a) right and b) left integrated EMG; airway c) flow (L/min) and d) pressure (cmH₂O) signals; e) right f) left MMG (m/s²) signals; and g) Stimulation pulse trains.

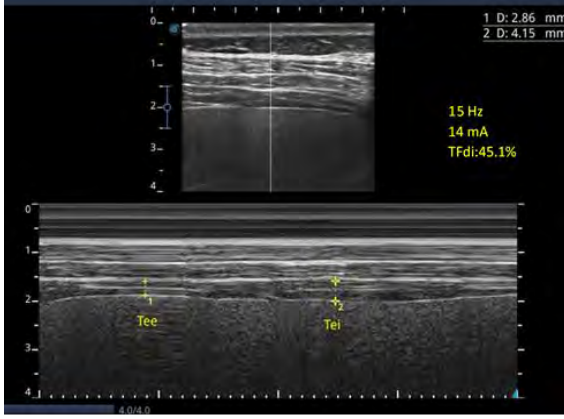


Figure 4: Diaphragmatic ultrasound assessment during phrenic nerve electrical stimulation.

mean value was 24 (14-38) mA for both nerves. The pulse widths had a mean value of 198 (150-280) us.

Figure 3 shows the results obtained during functional testing in one volunteer (stimulation parameters used were: 20 mA, 200 us, and 13 Hz). Ventilator parameters used were respiratory rate of 18 bpm, inspiration/expiration ratio of 1:2, 0 cmH₂O of PEEP, and pressure support of 4 cmH₂O. Representative diaphragm thickening fraction (TF_{di}), assessed by ultrasound in response to electrical stimulation, is shown in figure 4. Stimulation parameters used for this volunteer were: 14 mA, 200 us, and 15 Hz, obtaining a TF_{di} of 45.1%.

Discussion

Our results show the feasibility of using a non-invasive phrenic nerve stimulator to activate the diaphragm during non-invasive ventilation. Phrenic nerve stimulation generates effective diaphragm contraction as a spontaneous breathing effort that triggers the ventilator and keeping safety ventilatory parameters, similar to clinical context in assistive ventilation.

No adverse effects were found during the research. However, some volunteers reported discomfort during stimula-

tion periods, mainly pricking sensations because the adhesion of the electrodes to the skin was lost. Surface electrodes do degrade with time and change their impedance and adhesion. An automatic electrode impedance monitoring would be dealt with this problem.

The relatively superficial nature of the phrenic nerve within the cervical region enables the use of surface electrodes. However, surface electrodes have a big problem: the lack of selectivity, causing undesired activation close to the target zone. We observed that using an experimental prototype of a concentric ring electrode improved the stimulation selectivity, ensuring the phrenic nerve activation. Despite this, we found that proper diaphragm activation is highly dependent on the neck position during the testing. When the volunteer moves the neck, the electrode changed its position, losing the motor point. To overcome this problem, it was necessary to put some pressure on the electrode to achieve activation on multiple occasions. Even though the pressure was minimal, a method that allows maintaining or automatically adjusting the position of the electrodes during the sessions must be considered. That also could help the calibration process make it more efficient and effective. An electrode array with a concentric ring design having multiple cathodes is an option it is being explored. That may avoid the need to apply pressure on the electrode, obtaining an appropriate response and compensating for losses in the motor point caused by movement of the neck or position of the electrode.

The stimulation parameters are another aspect that is currently exploring. In this study, the parameters used were based on those typically applied in electrical stimulation systems and was limited by the stimulator design. Being a feasibility study, the prototype developed was limited to monophasic waveforms, and frequency and width pulse remained almost constant among the volunteers. Although the phrenic nerve was activated, it is necessary to explore the effect of the stimulation parameters. Furthermore, it was not possible to verify the impact of non-invasive stimulation on diaphragm function due to the short time of intervention.

The system proposed can detect ventilation phases in a clinical environment by the monitoring sensors (flow and pressure sensors), allowing a secure synchronization with

Table 1: Electrical stimulation parameter used during functional testing

Volunteer	Gender	Age	Frequency (Hz)	Pulse Width (us)	Right phrenic nerve amplitude (mA)	Left phrenic nerve amplitude (mA)
1	F	33	15	200	14	14
2	M	39	14	200	26	26
3	F	33	13	180	29	29
4	F	28	13	150	28	19
5	F	35	13	200	38	38
6	M	28	13	150	20	20
7	M	31	13	170	20	20
8	F	29	15	280	22	25
9	M	26	11	250	20	20
10	M	28	14	200	25	25

patient spontaneous efforts during the weaning process. These could represent further research directions.

The research team will implement a clinical trial in an ICU environment to test our approach for the next step. This clinical trial aims to study the feasibility and the effect of using electrical stimulation to maintain diaphragmatic functionality. Variables such as diaphragm thickness, weaning success, and the total time of stay in the ICU will be assessed.

Acknowledgement

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NON-INVASIVE PHRENIC NERVE STIMULATION TO AVOID VENTILATOR INDUCED DIAPHRAGM DECONDITIONING IN CRITICAL CARE: PARAMETER OPTIMISATION

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Abstract: *Diaphragm atrophy during mechanical ventilation begins within 24 hours and occurs rapidly with significant clinical consequences. Electrical stimulation of the phrenic nerve using invasive electrodes has shown promise in maintaining diaphragm function by inducing diaphragm contraction. However, application of these methods is limited by their risks as well as the technical and environmental requirements of placement and care. Non-invasive methods would offer a valuable method of maintaining diaphragm function while overcoming these limitations. We demonstrate that non-invasive capture of the phrenic nerve is feasible using surface electrodes without the application of pressure, and characterise the stimulation parameters required to achieve therapeutic diaphragm contractions in healthy volunteers. This opens the possibility of non-invasive systems, requiring minimal specialist skills to set up, for maintaining diaphragm function in the intensive care setting.*

Keywords: *Electrical stimulation, phrenic nerve, critical care, ventilator induced diaphragm dysfunction*

Introduction

Mechanical ventilation is an essential intervention in critical care medicine. However, disuse of the diaphragm during ventilation can rapidly result in severe atrophy [1]. This ventilator-induced diaphragm dysfunction (VIDD) is associated with difficulty weaning from mechanical ventilation and poor outcomes [2].

Stimulation of the phrenic nerve to induce diaphragm contraction is a promising means of maintaining diaphragm function during mechanical ventilation. Transvenous pacing has been shown to maintain diaphragm integrity in animals [3], while implanted [4] and percutaneous [5] stimulators have shown potential value in humans.

Invasive methods of phrenic nerve stimulation have a number of disadvantages. As well as requiring specific technical skills for implantation, limiting their widespread application, these methods carry risk during the implantation procedure as well as afterwards, and demand additional care to avoid displacement and infection.

Non-invasive stimulation of the phrenic nerve would offer a means of maintaining diaphragm function during mechanical ventilation while avoiding the risks and technical

limitations of more invasive approaches. The ability to induce diaphragm contraction using surface electrodes has been demonstrated, however these approaches rely on frames [6], collars [7,8] and hand-held probes [9] to apply pressure to fix the electrode in position and improve coupling between the electrode and the nerve. This is not suitable for extended use in an intensive care setting, where the constant pressure risks the generation of pressure sores on the neck.

Our group therefore aimed to develop a non-invasive stimulation system suitable for maintaining diaphragm muscle function in ventilated patients in an intensive care setting. We aimed to develop a system that reliably produces ventilator-synchronised diaphragm contraction using surface electrodes without the application of pressure.

This paper describes the work in Oxford towards a jointly managed project between Oxford, UK and Concepcion, Chile to achieve transcutaneous activation of the phrenic nerve. The work in Chile is presented in a second submitted paper.

In the accompanying paper, we outline the system design and demonstrate the feasibility of achieving ventilator-synchronised diaphragm contraction using surface electrodes. However, it remains unclear whether it is feasible to achieve reliable capture of the phrenic nerve with surface electrodes without the need for pressure. Further, it is unclear what the ideal stimulation parameters are, and how sensitive the response is to factors such as electrode location, head position and head movement.

Here, we investigated the feasibility of non-invasive stimulation of the phrenic nerves to induce therapeutic diaphragm contraction using a surface electrode array without the application of pressure. We demonstrated that non-invasive capture of the phrenic nerve is possible and characterise the parameters required to achieve meaningful diaphragm contraction in healthy volunteers. This opens the possibility for non-invasive methods to maintain diaphragm function in ventilated patients.

Methods

Healthy volunteers with no respiratory or neurological pathologies were recruited. The study was approved by the University of Oxford Central University Research Ethics

Committee (approval reference R73898/RE001). Electrodes were placed on the neck in the arrangement shown in figure 1. Six 1cm x 1cm cathodes (Axelgaard) were placed with 2mm intervals and surrounded by an anode with a typical electrode impedance of $1470 \pm 148\Omega$. The medial edge of the electrode array was placed on the midline with the cathodes at the level of the cricoid cartilage.

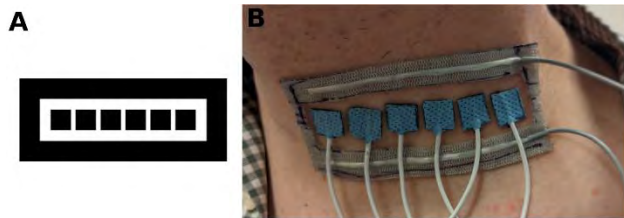


Figure 1: Electrode design. Central 1cm x 1cm cathodes are separated by 2mm intervals and surrounded by an anode. (A) Schematic of electrode design; six cathodes are surrounded by an anode. (B) Photograph of electrode arrangement in situ.

Stimulation was applied using a Digitimer DSR8 current-regulated stimulator with a compliance voltage of 400V. Biphasic, charge-balanced, symmetric waveforms were used throughout. Each of the six cathodes was attached to a Digitimer D188 electrode selector to allow stimulation at individual electrode sites.

Measuring diaphragm activity

Respiratory responses to stimulation were recorded using pressure and flow sensors attached to a pitot tube section of an anaesthetic circuit which subjects breathed through, forming a seal with the lips around its end. Subjects maintained an open glottis and wore a nose clip to prevent escape of air through the nose. The work done by the diaphragm was then computed by calculating the pressure volume work over the period following stimulation, i.e. $\int P dV dt$.

Assessing electrode position

The effect of electrode position was characterised by stimulating at each cathode sequentially at a range of amplitudes using single stimulation pulses while the respiratory response was measured. This was performed with the head centred and then while looking to the left or to the right in order to assess the effect of head position on optimal electrode placement.

Assessing stimulation parameters

The electrode that induced the lowest threshold response was selected. The strength-duration curve for the phrenic nerve was then characterised by measuring the threshold required to produce a measurable diaphragm response for a range of pulse widths using single stimulation pulses.

In a subset of participants, the effect of stimulation frequency was investigated by delivering 200 ms pulse trains of varying frequency at the optimal electrode using 100 μ s pulses at 125% of the threshold identified. The diaphragmatic pressure-volume work produced by stimulation was calculated and integrated over the 1s following stimulation to measure the effect of stimulation.

Results

14 participants were recruited (7 male, 7 female).

Electrode position

In all participants, one cathode showed a greater response than all the others, with a rapid drop in diaphragm response following stimulation at the neighbouring electrodes. An example of an electrode sweep over a range of amplitudes is shown in figure 2A, where one electrode shows a clear response, while there is a smaller response at neighbouring electrodes and little response at other electrodes.

The distributions of optimal electrodes across all participants for each head position are shown in figure 2B. Most participants (6/14) had a maximal response at electrode 5 (68mm from the midline), while 4 participants had a maximal response at the 4th (56mm from the midline) and 6th (80mm from the midline) electrodes. Notably, the optimal electrode did not vary with head position in any participant.

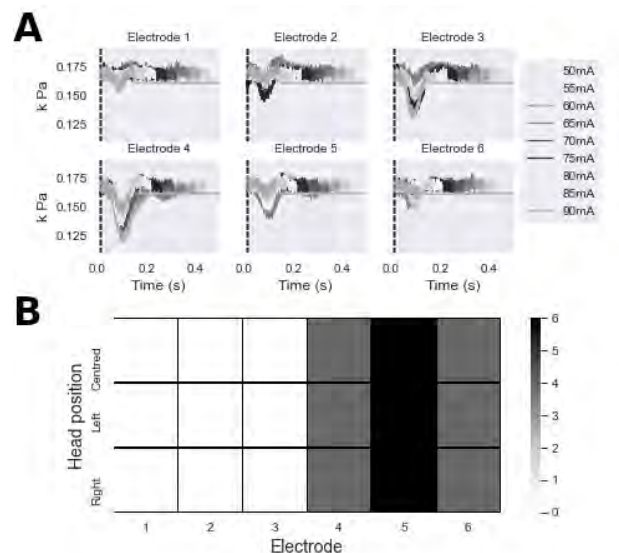


Figure 2: Effect of electrode position. (A) Example of differential pressure generated by single stimulation pulses at each electrode over a range of amplitudes. Response is sensitive to electrode positioning, with a rapid drop off in response between the optimal electrode and its neighbour. (B) Heatmap of optimal electrode position across participants; colour indicates the number of participants for which that electrode was optimal. Electrode 1 is most medial with electrode 6 lateral. All participants responded to one of electrodes 4-6; the optimal electrode did not change with head position.

Strength-duration relationship

Threshold amplitudes were variable across individuals. However, there was a decrease in threshold as pulse width increased in all participants. The mean strength-duration curve for the phrenic nerve using single stimulation pulses is shown in figure 3. This demonstrates a relative flattening of the threshold above a pulse width of 110 μ s.

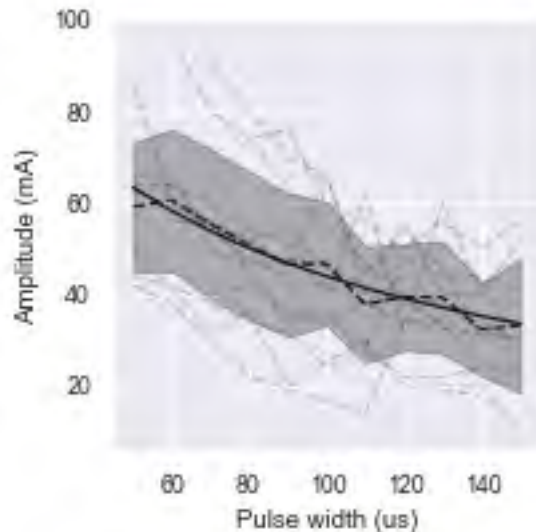


Figure 3: Strength-duration curve. A hyperbola fit to the strength-duration curves for all participants is shown as a solid line. The mean amplitude threshold across pulse widths ($n=14$) for single pulses is shown as a dotted line. The standard deviation is shown as the shaded region. The individual participants' strength-duration curves are shown as gray dotted lines. The amplitude required to induce diaphragm contraction decreases as pulse width increases.

Stimulation frequency

200 ms pulse trains of 100 μ s pulses at 125% of the threshold identified on strength-duration testing produced a measurable diaphragm contraction. The work produced by stimulation increased as stimulation frequency increased. An example of the measured power (W) following pulse trains at varying frequencies is shown in figure 4A. The total work (J) done during the induced contraction is shown in figure 4B. This increases as stimulation frequency increases, with a sharp increase up to 50 Hz, and an average work at 100 Hz of 0.17 ± 0.09 J, corresponding to an inhaled volume of 609 ± 92 ml.

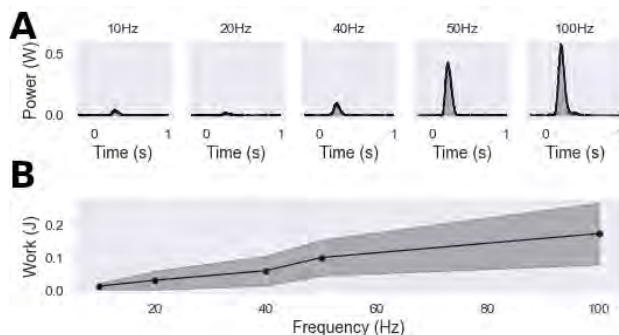


Figure 4: Effect of stimulation frequency on diaphragmatic work. (A) Example of diaphragm activity (W) following pulse train at a range of frequencies. (B) Diaphragmatic work done (J) following stimulation for a range of frequencies. Mean work done is shown. Standard deviation is shown as the shaded region. Increasing stimulation frequency induces greater diaphragmatic work.

Discussion

Our results indicate that non-invasive stimulation of the phrenic nerve for inducing diaphragm contraction is feasible, and we have characterised the stimulation parameters required for achieving reliable non-invasive activation of the nerve.

The ability to activate the phrenic nerve non-invasively is very sensitive to electrode position. Stimulation at the level of the cricoid cartilage reliably produced a response, but the lateral position required varied between individuals. All participants showed a response between 56mm and 80mm from the midline, with most responding at 68mm, but the individual optimum position was variable. This has important implications for practical application of this technique, as care must be taken to ensure electrodes are positioned appropriately.

However, our results also indicate that the optimal surface point for achieving nerve capture does not vary with head position. This is relevant for patients in intensive care, where proning patients can result in large variations in head position; our results suggest that electrodes will not need to be repositioned when the head is turned. Further, our results demonstrate that it is possible to identify the optimal electrode position from an array using measurements of the diaphragm response; this raises the possibility of automatic electrode selection from a surface array to account for inter-individual variability.

Our characterisation of the strength-duration relationship for non-invasive stimulation of the phrenic nerve and the relationship between stimulation frequency and inhaled volume provide a demonstration of the ability to achieve meaningful diaphragm contractions with non-invasive stimulation with parameters that are achievable with standard stimulation hardware. This further provides a valuable resource for the development of non-invasive stimulation systems by detailing the stimulation parameters required and their variability.

While our results were limited to the assessment of the use of pressure and flow measurements to assess the diaphragmatic response to stimulation, further work on other sensing modalities, such as lung sounds, may identify other methods of quantifying diaphragm activity and optimising response to stimulation. Further, while we can demonstrate reliable induction of diaphragm contraction in healthy volunteers, the ability to consistently produce sufficient diaphragmatic work to maintain function during mechanical ventilation in sedated, ventilated patients over the course of multiple days will need to be formally assessed, particularly as the electrode impedance changes over time may require electrode replacement in situations where ventilation is required for longer than one week [10].

Overall, these results support the potential clinical validity of non-invasive methods for maintaining diaphragm condition. While care must be taken to ensure accurate electrode placement, the stimulation parameters required are well within the range of standard stimulation systems and well within safe limits. This opens the possibility for non-invasive systems for maintaining diaphragm function in the intensive care setting, potentially improving ventilation

outcomes while avoiding the risks and technical limitations of more invasive stimulation techniques.

Acknowledgement

The authors would like to thank the National Agency of Research and Development (ANID), Chile. COVID-0925 and the University of Oxford University Challenge Seed Fund for supporting this research. This work was further supported by the National Institute for Health Research (NIHR) through the NIHR Oxford Biomedical Research Centre and the UK Engineering and Physical Sciences Research Council (EPSRC) via the University of Oxford Clarendon Fund. Additionally, it was supported by Project FONDEQUIP EQM150114 and FONDECYT 1201543. The views expressed are those of the authors and not necessarily those of the funding bodies.

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The effect of FES on gait kinematics and walking speed in people with MS under dual-tasking and fatiguing walking conditions

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Abstract: Several studies have indicated that while performing a cognitive task together with a walking task, people with multiple sclerosis (pwMS) exhibit deterioration in gait evidenced as reduced walking speed and associated reduced step length and increased double support time. Although many studies have investigated dual-tasking in pwMS, the influence of FES on the dual-task cost and the orthotic effect of FES have not been explored. The overall aim of the present study was to investigate the dual-task cost and the orthotic effect of FES under conditions which may be more ecologically valid than a single task, short duration laboratory walking test conventionally used to investigate the effects of FES in gait. Walking with the assistance of FES resulted in an improvement in all gait parameters and especially the peak dorsiflexion in swing. The dual task cost of walking speed was higher in MS (12.4%) compared to the healthy group (4.6%). Further investigation with a bigger sample size is required to confirm these findings.

Keywords: foot drop, FES, orthotic effect, dual-task, fatigability

Introduction

One of the benefits of Functional Electrical Stimulation (FES) as reported by people with multiple sclerosis (pwMS) is that it reduces the mental effort of walking, as less concentration is needed on the walking task [1,2]. Several studies have indicated that pwMS exhibit gait deterioration while performing a cognitive task together with a walking task [3-5]. Although many studies have investigated dual-tasking in pwMS, the influence of FES on the dual-task cost (DTC) and the orthotic effect of FES have not been explored. The aim of this pilot study was to investigate the effect of FES under conditions that simulate activities of daily living.

Methods

Participants were community walkers who experienced foot drop diagnosed by a physiotherapist and were using FES to treat foot drop. Further, eligibility criteria for the pwMS were clinically definite diagnosis of MS according to the revised McDonald criteria [6], aged 18 years and over and characterized with moderate to severe disability according to Expanded Disability Status Scale (EDSS \geq 4.0). Participants were excluded from the study if they had a clinically diagnosed relapse within the last month and had

any musculoskeletal impairments and cardiopulmonary disorders that could affect their walking ability.

Participants in the healthy control group were aged 18 and over and were also free from the diagnosis of any neurological disease or any other condition/injury that would affect their walking ability.

The study protocol required participants in the MS group to visit the motion analysis laboratory on two occasions. The purpose of the first visit was to record anthropometric characteristics required for the processing of 3D gait analysis data, such as height, body mass, leg length, knee and ankle width and tibial torsion. Also, in this first visit participants performed a few practice trials of the Stroop test [7]. The Stroop test is an attention-demanding task that 'assesses the ability to inhibit cognitive interference which occurs when the processing of a stimulus affects the simultaneous processing of another attribute of the same stimulus' [8]. In this test, participants were shown a word ('blue', 'yellow', 'red' or 'green') written in a different color (blue, yellow, red or green) and were instructed to state the color of the text and ignore the meaning of the word itself. The font of the letters was large enough for the participants to read from a seven-meter distance and a new word was displayed every second.

In the second visit participants performed the walking tasks (single and dual-task) and the physically demanding procedure to induce fatigability to assess the direct orthotic effect of FES. Participants were asked to complete a total of 24 short (approximately 7m) walking trials under three different conditions: A) single-task walking (FES on & off), B) dual-task walking (FES on & off) and C) dual-task walking after induced fatigability (FES on & off). An incremental shuttle walk protocol was used to induce fatigability. The walking trials of the first and second condition (single-task vs dual-task) with FES on and off were counter-balanced, so that a potential order effect was avoided. The dual-task cost (DTC) of walking speed for both groups was calculated using the following formula:

$$DTC_{ws} = \frac{(WS \text{ single task} - WS \text{ dual task})}{WS \text{ single task}} \times 100$$

The median and the interquartile range (IQR) was reported for all the outcomes. The percentage DTC_{ws} is reported for both groups. Further, on an individual level graphs are presenting the direct orthotic effect of FES of both dual-task and dual-task after induced fatigability compared to baseline orthotic effect. To investigate fatigability-induced changes in both groups, the median and IQR are reported for the conditions of dual tasking before and after the fatiguing (incremental shuttle) task.

Results

Seven pwMS and five healthy age-matched controls participated in the present study. All the pwMS were current FES users, with an EDSS range of 4 to 6. The two groups had a similar female to male ratio (MS 5 female/2 male; healthy controls 4 female/1 male) and average age in years (MS 54.1yrs, sd. 10.4/ healthy controls 55yrs, sd. 11.6).

A. Dual-task cost of walking speed

Both groups had a positive DTC_{WS} , with a positive percentage change indicating that there was a decrease in the walking speed from the single to dual-task condition. However, it can be seen from the data in Tab. 1 that the DTC_{WS} in the MS was on average 8% higher compared to the healthy control group.

Table 1 Percentage DTC_{WS} of the MS and healthy control group (presented as means and SDs).

Participants	WS (m/s)	WS _{DT} (m/s)	DTC_{WS} (%)
MS (n=7)	0.77 (0.4)	0.67 (0.4)	12.4 (11.5)
HC (n=5)	1.26 (0.2)	1.20 (0.3)	4.6 (7.8)

B. Direct orthotic effect of FES

Tab. 2 presents the medians (IQR) of peak dorsiflexion in swing and walking speed in the three conditions. When FES was off, both peak dorsiflexion in swing and walking speed decreased with increased task difficulty (A>B>C). It is evident that walking with FES-on resulted in an improvement, i.e. a direct orthotic effect.

At an individual level, for peak dorsiflexion in swing, six out of seven had a higher direct orthotic effect during the dual-task compared to the single-task condition whilst

Table 2 Median (IQR) of peak dorsiflexion in swing of the most affected leg (DFMA) and walking speed (WS) in the three conditions (with FES off and FES on the MS group). The effect size is based on the direct orthotic effect between the three conditions.

	Task A		Task B		Task C	
	FES off	FES on	FES off	FES on	FES off	FES on
DFMA (°)	3.1 (10.1)	6.8 (7.2)	1.3 (11.8)	5.9 (6.3)	0.3 (9.4)	6.9 (6.1)
WS (m/s)	0.8 (0.67)	0.88 (0.6)	0.76 (0.59)	0.8 (0.45)	0.57 (0.41)	0.69 (0.4)

The individual graphs of the participants for the direct orthotic effect of walking speed showed that three out of seven pwMS had a higher effect during the dual-task condition but only for two out seven after completing the fatiguing task (Fig.3 & Fig.4).

five out of seven had a higher direct orthotic effect after the fatiguing condition compared to the single task condition (Fig.1 & Fig.2).

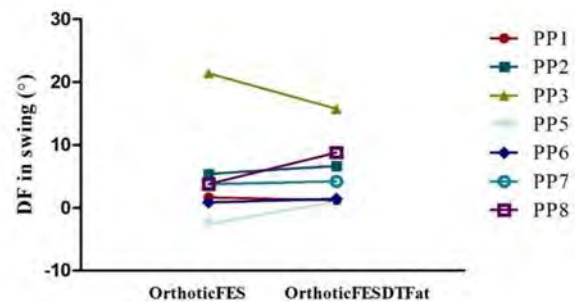


Figure 1 The direct orthotic effect on peak DF in swing between Task A (OrthoticFES) and Task B (OrthoticFESDT).

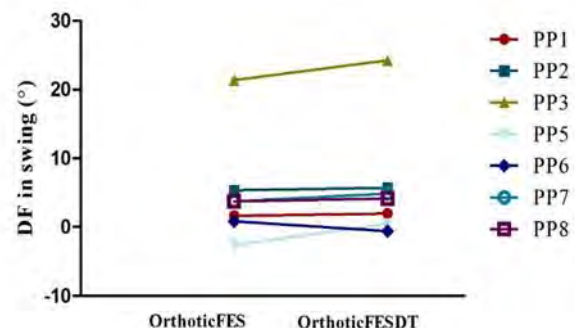


Figure 2 The direct orthotic effect on peak DF in swing between Task A (OrthoticFES) and Task C (OrthoticFESDTFat).

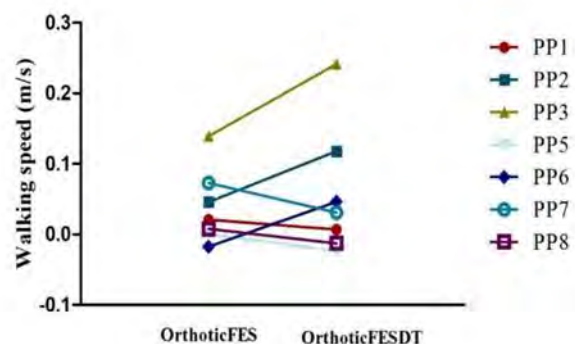


Figure 3 The direct orthotic effect on walking speed between Task A (OrthoticFES) and Task B (OrthoticFESDT).

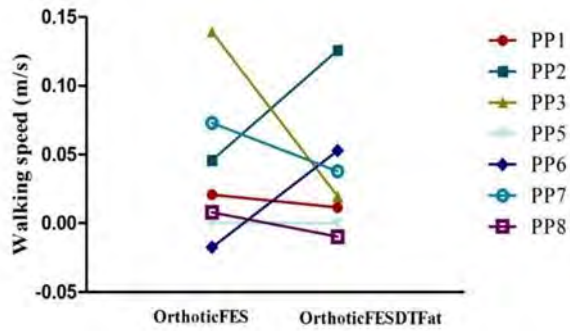


Figure 4 The direct orthotic effect on walking speed between Task A (OrthoticFES) and Task C (OrthoticFESDTFat).

C. Fatigability induced gait changes under dual-task conditions

Tab. 3 provides the medians (IQR) before and after completing the fatiguing task for peak dorsiflexion in swing and walking speed of the two groups. It is apparent from this table that on average pwMS had slightly decreased peak DF in swing (1°) after inducing fatigability and walked 25% slower in the fatigued dual-task condition compared to the unfatigued condition. Healthy controls did not seem to have worsened performance in the fatigued condition.

Table 3 Fatigability induced gait changes in peak dorsiflexion in swing of the most affected leg and walking speed during dual tasking in pwMS (without FES) and healthy individuals (presented as medians and IQR).

Task		MS (n=7)	HC (n=5)
DFMA ($^\circ$)	UnfatiguedDT	1.3 (11.8)	9.0 (5.5)
	FatiguedDT	0.3 (9.4)	9.2 (7.2)
WS (m/s)	UnfatiguedDT	0.76 (0.59)	1.10 (0.49)
	FatiguedDT	0.57 (0.41)	1.24 (0.41)

Discussion

To the authors' knowledge this is the first study to investigate the benefits of FES under dual-tasking and fatiguing conditions in pwMS. The findings suggest that there is an increased DTC_{WS} in pwMS compared to healthy controls. A direct orthotic effect of FES during dual tasking was found for most participants, but this was less evident in the fatigued condition. However, there is variability especially in the fatigued condition that makes it difficult to draw definite conclusions. Notwithstanding the relatively limited sample, this study offers valuable insights into the benefits

of FES reported by pwMS, such as that FES reduces the mental effort of walking. Further appropriately powered studies need to be carried out to investigate the benefits of FES under dual-task and fatigued conditions and possibly under more demanding dual-task conditions.

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CAPABILITIES OF FULL-BODY WEARABLE TESLASUIT AS A SELF-STANDING FES DEVICE – EXPLORATORY STUDY

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Abstract: Functional electrical stimulation (FES) devices are widely used in rehabilitation. Generally, FES systems could be classified into three groups: open loop, finite state control and closed-loop approach. The aim of this study was to explore possibilities to use the full-body wearable Teslasuit technology as a self-standing FES device as an open-loop, finite-state control, or closed-loop system.

Material and methods: A full-body Teslasuit v.4.5.5 with a standard electrostimulation system of 80 channels and motion capture system with 14 inertial measurement unit (IMU) sensors was used for this study. The suit was operated through standard Teslasuit software and, if necessary, extended through API to implement the functionality of main types of FES devices (based on a general description of these types). We performed a qualitative assessment (yes/no) of minimum feasibility for each approach and discussed the implementations' pros and cons.

Results and conclusions: The full-body Teslasuit technology can be used as a self-standing FES device, in some cases, even as an out-of-the-box solution. Feedback from medical experts is desired for further improvements as well as validation in clinical settings.

Keywords: open-loop system, finite-state control, closed-loop system, Teslasuit, Motion Capture

Introduction

Functional electrical stimulation (FES) devices are widely used in rehabilitation after spinal cord injury, stroke, multiple sclerosis, cerebral palsy etc., through low-energy electrical pulses to generate body movements artificially. There are several ways to classify FES systems, and for this overview, we use classification by mechanisms of stimulation control with well-established terminology used elsewhere [1]. Accordingly, FES systems could be classified into open loop, finite state control and closed-loop systems [1,2]. Moreover, these three approaches describe the staging or evolution of FES systems from simple to more sophisticated.

An open-loop system approach is the most straightforward way of stimulation control: a predefined stimulation pattern or a battery of patterns are triggered by an operator using the "start" button. A vivid example of a device using this approach being commercially available is Parastep [3]. The open-loop approach does not have any flexibility for example in terms of automatic start or stimuli duration correction and, therefore, devices mainly differ by patterns themselves or the variance of the start button [4]. Nevertheless, the open-loop approach and subsequent devices have a leading position in terms of availability partly due to their simpleness, long history and solid body of evidence.

A finite-state control approach introduces terms of input events or states detected from a constant data flow from the device. These events and states can start a predefined stimulation pattern. A sequence of input events can also have an interstates transition function [5]. All in all, the finite-state control approach seems to be an intermediate between the open and the closed-loop control approaches.

A closed-loop devices rely on control systems theory when simple triggering stimulation patterns are additionally tuned by the devices using sensed data in real-time. The closed-loop approach is very popular for MSc and PhD works studying changing environments, adaptation to muscle fatigue, electrode placement and contact, or dynamically changing FES [6].

Teslasuit smart full-body suit as part of the technology was designed to improve the user's motor skills through electro-stimulation using rich real-time data sensed by motion capture and biometry interfaces of the suit. The technology is used together with Virtual and Augmented Reality applications in different areas for professional and enterprise training since 2018. It has been hypothesized all technical capabilities of the suit could be utilized in medicine and rehab, specifically as a FES device.

This exploratory study aimed to check the capabilities of full-body wearable Teslasuit technology as a self-standing FES device. In particular, we aimed to confirm that Teslasuit can be used as an open-loop, finite-state control or closed-loop system.

Materials & Methods

For this study, we used a full-body Teslasuit v.4.5.5, Teslasuit software development kit v. 1.2.7 (SDK, consists of Haptic Editor tool and Suit client API) and external operating code when needed. The full-body Teslasuit is equipped with a standard electrostimulation system consisting of 80 channels (16 for every extremity and 16 for the back and belly, see Fig. 1) and a markerless motion capture system with 14 inertial measurement unit (IMU) sensors (MoCap system, Fig. 2). Haptic editor tool allows to create, tune, and run stimulation patterns with various



Figure 1. Placement of EMS electrodes in full-body wearable Teslasuit v. 4.55



Figure 2. Placement of IMU sensors in full-body wearable Teslasuit v. 4.5.5

signal parameters for each of the 80 EMS channels with fixed voltage of 60 volts: stimulation frequency could be tuned in the range of 1 to 150 Hz, and stimulation pulse width in 1-320 microseconds range (Fig. 3). Suit client API was used to access the MoCap data stream (30FPS) and to control EMS systems if needed.

To test whether Teslasuit technology can be used for FES we use the general description of different FES approaches and reproduce functionality using built-in functionality of the technology or extend it with additional external functions through Suit client API (using Framework and Python 3.9) in the form of minimum viable products (MVPs).

All tests were performed on the authors or colleagues, i.e. healthy volunteers working in the Company.

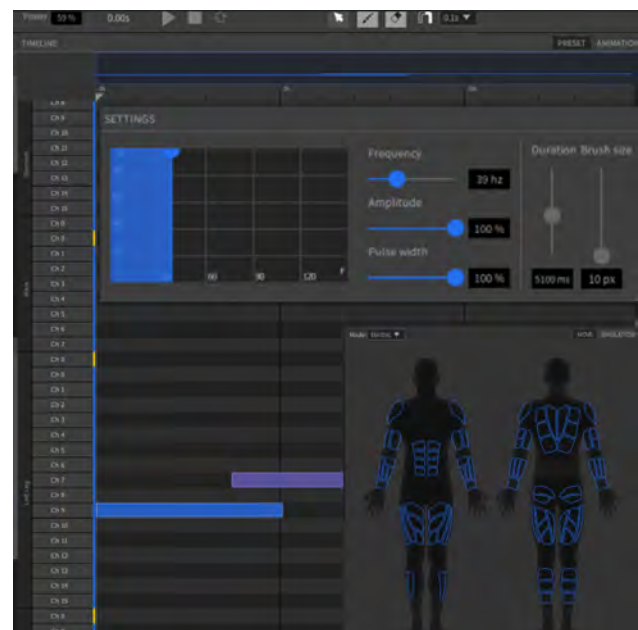


Figure 3. Controlling interface of Haptic Editor (Teslasuit SDK v. 1.2.7) used to configurate EMS patterns for various FES applications

Results and discussion

For coherence and simplicity of the report results and discussion are joined for each of the approaches in one session.

Teslasuit as an open-loop FES device

The Haptic Editor tool can perform tasks like running stimulation electrical patterns on target anatomical areas triggered by an operator. Simple case scenario includes: wearing the suit on a test subject, connecting the suit to computer and Haptic editor, calibration of the suit EMS system (i.e. set minimum effecting and maximum “still-not-painful” levels as 0 and 100% effective range limits, respectively), creating and tuning EMS stimulation patterns in Haptic editor, running stimulation patterns looped in time or by start button clicking (repeated or single events). Besides, the virtual start button in Haptic

editor could be replaced with a real-world mechanical button or another trigger (as a third-party device through the API). Moreover, Haptic editor allows to create complex stimulation patterns varying different electrical parameters in time within any EMS channel or combining stimulation patterns between all 80 EMS channels. All these patterns can be saved as files for later use with the same or other test subjects.

There are several system features which could be treated as limitations or advantages:

- the form and placement of EMS electrodes are predefined and cannot be changed – standard position of electrodes incorporated in the full-body-suit allows decrease preparation time and increase consistency between FES sessions;
- hardware and software limits of ranges of EMS parameters (might be not enough in some group of patients i.e. after spinal cord injury) – end-user safety against pain or injury (temporary or constant electrical trauma);
- the current version of the textile base is not ideal for long-term FES sessions and might be challenging to wear in certain groups of patients – the current study and set-up are exploratory and give us a vision of how to improve the suit further to solve these issues.

It is important to acknowledge, that Haptic editor as tool for visual creation of complex stimulation patterns gives almost limitless possibilities to adjust Teslasuit technology to any needs as open-loop FES device. Moreover, visual control and turning of EMS patterns in Haptic Editor decrees learning threshold and make it easier to start and use for specialist in medicine, rehab and research.

Therefore, Teslasuit technology is capable to be used as an open-loop FES device as out-of-the-box-solution without additional extension, however, for research purposes only. There is a space for certain improvement of some product aspects which, however, might be very task specific and, therefore, should be done in coordination with medical experts in the field.

Teslasuit as a finite-state FES device

To prove concept of our technology being used for finite-state FES we used motion capture interface with its applied data processing solution called “Step detector”. Step detector provides information about foot-floor contact for each foot separately. This time-series data is enough to properly detect 4 walking phases (corresponding to simplified GAIT cycle, see Figure1): initial contact and terminal stance as well as initial swing and terminal swing. Using Accordingly, we assigned simplified electrical stimulation patterns same as on Figure 1B. At the beginning of the stance, we initiate Plantarflexors contraction, then initiate and hold Dorsiflexors contraction during whole swing phase. Also, after initial swing we initiate quadriceps contraction to extend the leg and, optional, before the terminate swing run the humstrings to stabilize leg a bit and prevent making a step on fully extended extremity.

Simple case scenario starts wearing and connecting the suit, as well as calibration of EMS system and follows with MoCap calibration. Preparation steps are followed by run of external program “walking FES” (MVP works through API). Exact parameters of EMS as well as target EMS channels could be changed in Haptic Editor and then loaded to the MVP.

Most of the discussion points from open-loop approach are “inherited” in this MVP. Likewise, since finite-state systems heavily rely on input data, and nevertheless, observed results were stable and repeatable, additional validation of MoCap system providing a set of step detection triggers have to be performed. More sophisticated MoCap data such as ankle angles, angular velocity, angular acceleration could be tested as alternative triggers. For end-user usability all functionality of the MVP (i.e. calibrations, EMS patterns editor and running interface itself) ideally should be joined in our self-standing program.

As an intermediate conclusion, we can say that Teslasuit technology is capable to be used as a finite-state FES device.

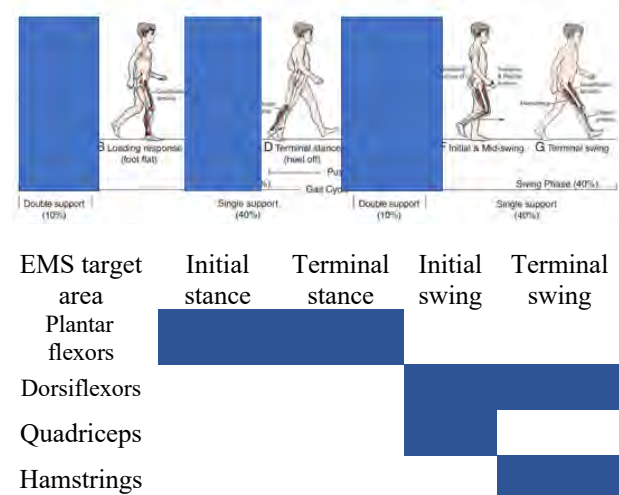


Figure 4. Schematic description of simplified walking FES implementation and corresponding EMS patterns

Teslasuit as a closed-loop FES device

To prove the concept, we constructed MVP based on simplified closed-loop control concept for straightforward task of elbow flexion control (fig 2). MoCap from the suit provides real-time data of the current elbow angle, which was then compared the target value (set by the operator). The difference between the current and the target angel as a resulting error is processed by the PID controller, which adjusts the required level of biceps stimulation. As for now we use a muscle response function with further use of the classic Ziegler-Nichols method for selecting the

coefficients of the PID controller to solve question of the PID controller calibration algorithm for each specific user. Simple case scenario in addition to wearing/connecting the suit and EMS calibration includes PID controller calibration which is performed in external program “elbow FES” (MVP works through API).

Therefore, results from all test subjects were repeatable and stable and Teslasuit technology shows potential to be used as a closed-loop FES device. Nevertheless, there is a potential to improve this MVP and recommendation from medical FES experts are essential for improvement of the product.

Conclusions

In this exploratory study, we have shown capabilities and potential of full-body Teslasuit to be used self-standing FES device (including an open-loop, finite-state control or closed-loop approaches). Specifically, Teslasuit as the open-loop FES device could work as an out-of-the-box-solution for research purposes. Further improvements and development should go in close collaboration with medical FES experts as well as additional validation in clinical settings is needed.

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EFFECTS OF NEUROMUSCULAR ELECTRICAL STIMULATION ON BLOOD PRESSURE IN INDIVIDUALS WITH SPINAL CORD INJURY

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Abstract: Chronic orthostatic hypotension (OH) is a common problem in individuals with high-level spinal cord injury (SCI). Neuromuscular electrical stimulation (NMES) of paralyzed abdominal and leg muscles could be a method to help alleviating this problem. The aim of this pilot study was to compare blood pressure (BP) responses to 1-hr NMES of the abdominal muscles, the leg muscles and of these muscles combined with the individual in sitting position. BP of 5 individuals with SCI and 5 able-bodied individuals (AB) was measured during 3 1-hr sessions on separate days. NMES was applied using a full-body suit with built-in surface electrodes (Teslasuit). Variability in responses was large. No significant changes in BP were observed in the AB, while in the SCI group systolic (and to a lesser extent diastolic) BP significantly increased from and remained on average 10-15 mmHg above resting levels during NMES of the legs, and legs and abdominals combined, but not during NMES of only abdominals. While optimal stimulation parameters are still unknown, these preliminary results suggest that NMES of leg and abdominal muscles could have the potential to help alleviating chronic OH in individuals with high-level SCI.

Keywords: Orthostatic hypotension, tetraplegia

Introduction

Individuals with high-level spinal cord injury (SCI) lose the ability of tonic activation of sympathetic preganglionic neurons in the splanchnic area, leading to a disrupted baroreceptor reflex for vasoconstriction below the injury level. This, in combination with a disturbed skeletal muscle pump, often results in low venous return and chronic low resting blood pressure (BP) and an inability of BP adaptation during orthostatic challenges such as sitting [1,2,3], possibly leading to symptoms such as lower cognitive function, light-headedness, headache, sleepiness, fatigue, fainting and poor concentration [4]. Proper treatment of OH is, therefore, needed. Neuromuscular electrical stimulation (NMES) evokes muscular contractions and vasoconstriction in the extremities [5] and the splanchnic area, causing redirection of blood flow to the heart, potentially increasing BP. It is currently unknown which muscle groups can be best stimulated to alleviate OH in this population. The aim of this pilot study, therefore, was to compare BP responses to 1-hr NMES of the abdominal muscles, the leg muscles and these muscles combined with the individual in sitting position, both in SCI and able-bodied (AB) participants.

Methods

In this pilot study, we measured during 3 visits the participant's BP during sitting with no stimulation applied, and in 3 NMES conditions: NMES applied to the abdominal wall (ABS), lower extremities (LEGS) and both abdominal wall and lower extremities combined (BOTH).

Participants: 5 AB (age 26±2 yr) and 5 SCI (age 47±8 yr, time since injury 1.5-25 yr, lesion levels C4, C4-5, C4-5, C5, T2-4, complete 1) individuals.

Experimental setup and protocol: During each visit, participants started 20 minutes sitting in rest, followed by 1 of the 3 1-hr NMES conditions. NMES was provided by a full-body suit with built-in surface electrode pairs (Teslasuit v. 4.5.4, VR Electronics Ltd, London, UK). Stimulation parameters were 30 Hz, 1 ms pulse duration, amplitude individually adjusted to induce noticeable but comfortable contractions, and a duty cycle of 1s stimulation, 1s rest. For the SCI individuals the power was 35-85% of max (150mA) and for AB much lower, i.e. between 28-35%. When stimulating the abdominal wall, stimulation was applied to the rectus abdominis, and stimulation at the lower extremities was applied simultaneously to the ankle, knee and hip flexors and extensors (Fig 1).

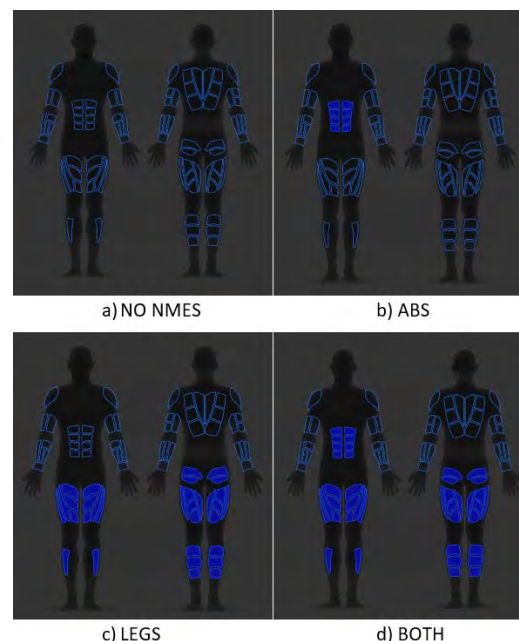


Figure 1. Electrodes placement in the 4 conditions with the blue areas being stimulated.

Blood pressure measurements: BP was measured with an automatic device (OMRON, M6 (HEM-7001-E(v))) with the cuff placed around the left arm (Fig. 2). Baseline systolic (SBP) and diastolic BP (DBP) was collected during rest before each experimental condition and subsequently every 5 minutes during the 1-hr NMES. Acute responses were determined during the first 10 min after applying NMES, delayed responses during the last 10 min as well as 1-hr averages.



Figure 2: Experimental setup with the participant sitting in his wheelchair and wearing the Teslasuit for stimulation of abdominal wall and/or lower extremities.

Statistical analysis: One-way repeated measures ANOVA were applied to detect differences in acute, delayed and average BP responses for the different NMES conditions for the 2 groups with an α of 0.05.

Results

While BP did not statistically significantly change during NMES in the AB group, BP increases were obvious in most SCI individuals with the most marked increases in the LEGS and BOTH conditions, while responses differed markedly among SCI participants. Fig. 3 shows examples of the 1-hr BP values in the SCI group. During the first 10 min of LEGS ($p < 0.05$) and BOTH ($p = 0.07$), SBP increased by 17 ± 15 and 22 ± 28 mmHg, resp., declined towards the last 10 min while remaining statistically non-significantly above resting levels, with the average values 10-15 mmHg above baseline (Table), which was statistically significant ($p = 0.03$) for the LEGS condition. A similar pattern, with lower responses, were noted for DBP with a tendency ($p = 0.06$) towards a statistically significantly higher average DBP during the LEGS condition.

Discussion

This pilot study in a small group of individuals with high-level SCI shows that NMES to the paralyzed abdominal and leg muscle can increase BP. No responses were found in the AB group, which can be largely explained by the lower stimulation levels applied since they have full sensation. The most effective NMES location for BP increase appeared to be the legs. Using the skeletal muscle pump probably increased venous return and prevented blood pooling in the veins of the legs, and hence increased BP with about 10-15 mmHg during the 1-hr stimulation. Whether this increase can counteract OH and concomitant problems needs to be investigated.

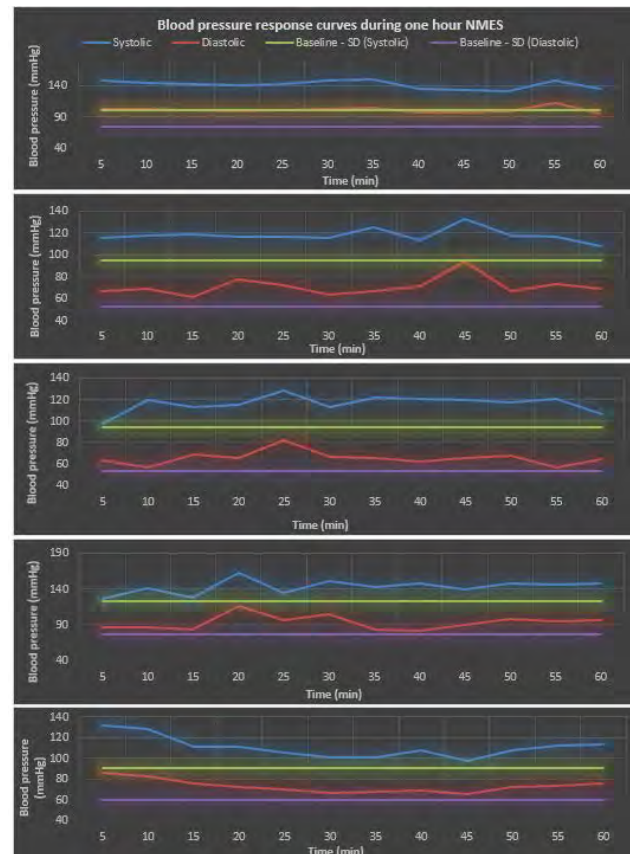


Figure 3: Selected BP curves from the SCI group. Graphs 1,2,4 (from top) Condition LEGS, graphs 3,5 Condition BOTH.

NMES of the abdominals did not markedly increase BP, which is not in line with a study by Kouwijzer et al. [6]. However, they stimulated not only the rectus abdominis (as we

Table: Average SBP and DBP values per group and condition.

		Systolic BP (mmHg)				Diastolic BP (mmHg)			
		Baseline (No NMES)	First 10 min (Δ Acute response)	Last 10 min (Δ Delayed response)	One hour average	Baseline (No NMES)	First 10 min (Δ Acute response)	Last 10 min (Δ Delayed response)	One hour average
Able bodied	Abs	108 \pm 12	107 \pm 10 (-0.8 \pm 4.8)	102 \pm 8 (-6.2 \pm 9.4)	106 \pm 9	65 \pm 6	66 \pm 3 (1 \pm 5.5)	67 \pm 3 (2.2 \pm 3.6)	66 \pm 4
	Legs	111 \pm 14	109 \pm 15 (-1.8 \pm 4.8)	108 \pm 13 (-3.1 \pm 2.7)	107 \pm 14	69 \pm 7	67 \pm 6 (-1.5 \pm 11.5)	66 \pm 2 (-3.1 \pm 7.8)	66 \pm 6
	Both	110 \pm 12	110 \pm 15 (-1.0 \pm 5)	109 \pm 12 (-1.2 \pm 3.1)	109 \pm 13	68 \pm 4	68 \pm 4 (-0.3 \pm 2.1)	67 \pm 4 (-1.3 \pm 3.9)	67 \pm 4
Spinal cord injured	Abs	108 \pm 12	112 \pm 15 (4 \pm 8.1)	107 \pm 12 (-0.1 \pm 4.7)	108 \pm 14	71 \pm 10	72 \pm 10 (1.1 \pm 3.9)	73 \pm 9 (2.1 \pm 4.3)	72 \pm 11
	Legs	111 \pm 14	128 \pm 13 (17 \pm 15)	121 \pm 22 (10 \pm 14.4)	126 \pm 20	72 \pm 8	78 \pm 17 (5.5 \pm 11.2)	80 \pm 19 (7.6 \pm 10.6)	78 \pm 14
	Both	111 \pm 16	133 \pm 25 (22.5 \pm 28.5)	120 \pm 17 (9.7 \pm 18.1)	121 \pm 15	74 \pm 13	80 \pm 17 (6.6 \pm 12.1)	75 \pm 12 (1.3 \pm 8.8)	79 \pm 15

did), but also the obliquus externus abdominis and the erector spinae, which may explain the increased BP they found in individuals with tetraplegia. The current version of the garment used did not allow activation of these muscles, but more recent versions will.

As expected, responses varied considerably among participants, which in part can be explained by differences in a.o. completeness of the lesion, sensory deficits, BP resting levels, and muscle contraction levels. An individual approach to identify an optimal stimulation protocol may be necessary. The full-body suit with 80 electrode pairs and versatile software seems not only suitable to realize this, but may also be used to evaluate the effects of various stimulation parameters, different muscle groups stimulated, and of long-term use.

Activating the paralyzed leg and abdominal muscles may not only be beneficial for alleviating chronic low BP, but might also improve the condition of muscle and nerve tissue, circulation, sitting pressure distribution, and reduce risk of secondary complications such as pressure sores [7].

Conclusion

While optimal stimulation parameters are still unknown, these preliminary results suggest that NMES of leg and abdominal muscles could have the potential to help alleviating chronic orthostatic hypotension in individuals with high-level spinal cord injury.

Acknowledgement

Thank you to all the participants for their time, patience and cooperation. A big thank you also to Bob Koomen and to the rest of the staff in the rehabilitation centre Reade, Amsterdam, for helping with the recruitment and measurements.

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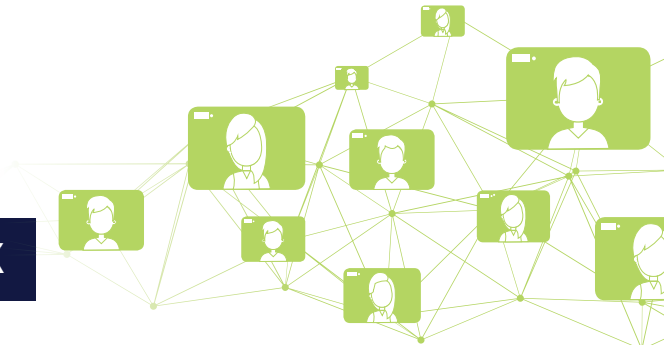
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ABSTRACT E-BOOK



Type of submission: Scientific Poster

Preliminary Validation of an Adaptive Robotic Training Program of the Hand and Wrist for Persons With Multiple Sclerosis

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Presenting author: Mannella, Kailynn

For persons with multiple sclerosis (MS), sensorimotor function and movement may be impaired causing overall upper limb dysfunction [1]. Robotics can objectively quantify wrist kinematics and its intrinsic mechanical properties (stiffness, inertia), which can be biomechanical markers related to improvements in neuromuscular control [2]. In this pre-post study design, 7 individuals with MS completed a robotic training program that occurred 3 times per week for 4 consecutive weeks. Using the WristBot [3], participants placed their forearm in the device grasping the handle with the most affected limb and tracked a figure 8-shape by tracking a moving target on the computer screen. Robotic software was adaptive and every 3 laps the average kinematic performance was calculated and used to modify the robotic assistance/resistance throughout the training program. Improvements in performance were quantified by average tracking and figural error, which was significantly reduced from pre-post intervention by 26% and 43%, respectively. Isometric wrist strength significantly improved post-intervention (flexion: 2.8kg, radial 3.7kg and ulnar deviation 2.5kg). Grip force endurance increased by 60% post-intervention. This study highlights a novel adaptive and individualized robotic rehabilitation program providing both assistance and resistance to the distal upper extremity for individuals with MS. Results of this work provide a proof-of-concept that motor control and muscular strength can be improved by this type of rehabilitation modality. The adaptive training approach used in this work has demonstrated effective individualization of the therapy process with assistance levels and progressions for various types of MS, severity of disease and age levels. This work provides insight that robotics for rehabilitation of the distal upper limb for a MS population can yield beneficial results and combined with conventional therapy might promote increased motor control and motor function.

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A PRELIMINARY EVALUATION OF A HAND AND WRIST ROBOTIC TRAINING PROGRAM FOR PERSONS WITH MULTIPLE SCLEROSIS

Kailynn Mannella, Giulia A. Albanese, Jacopo Zenzeri, Michael W.R. Holmes

Motivation for Research

- Upper limb disability is present in 66% of patients that are diagnosed with multiple sclerosis (MS) (Zhong, 2016)
- Robotics can be used to accurately assess wrist kinematics and sensorimotor impairments, while also implementing adaptive algorithms aimed at improving neuromuscular control (Falzarano et al., 2020)
- Little research exists on robotic upper extremity neurorehabilitation for individuals with MS
- The proposed training program aimed to improve wrist motor accuracy of persons with MS by implementing an online modulation of the assistance during a tracking task

Methodology

- 7 participants with MS were recruited (age: 46.9 ± 15.9 years, EDSS: 4.7 ± 1.8, years since diagnosis: 4.6 ± 10.3 years)
 - Relapsing Remittent MS (n=3)
 - Secondary Progressive MS (n=3)
 - Primary Progressive MS (n=1)
- Participants traced a figure-8 curve by manipulating a custom built robotic device (WristBot, Genoa, Italy)
- Real-time robotic adaptation; evaluated figural error and modified assistance/resistance based on performance
- Robotic training (of the most affected limb) occurred 3x/week for 4 weeks (Figure 1)

Assessments

- Time 1
- Week 1 - Pre-intervention
- Time 2
- Week 4 - Post-intervention

Outcome Measures

- Maximum Grip Force
- Passive/Active ROM
- Active Tracking Accuracy
- Maximal Iso Wrist Force
- Grip Force Endurance
- 9-Hole Peg Test

WristBot

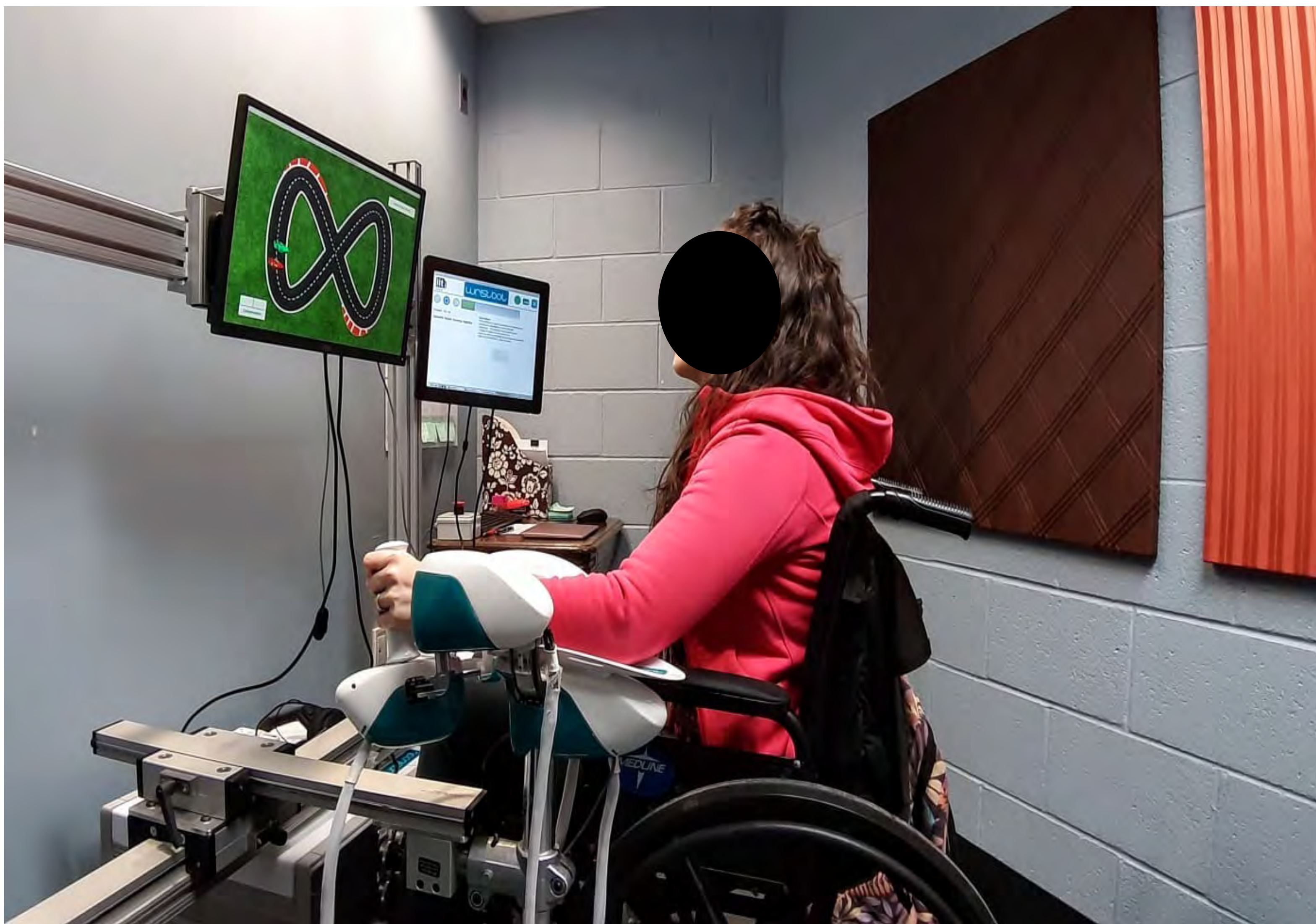


Figure 1. Experimental set-up with the participant grasping the handle to perform the tracking task with visual feedback

Experimental Procedure

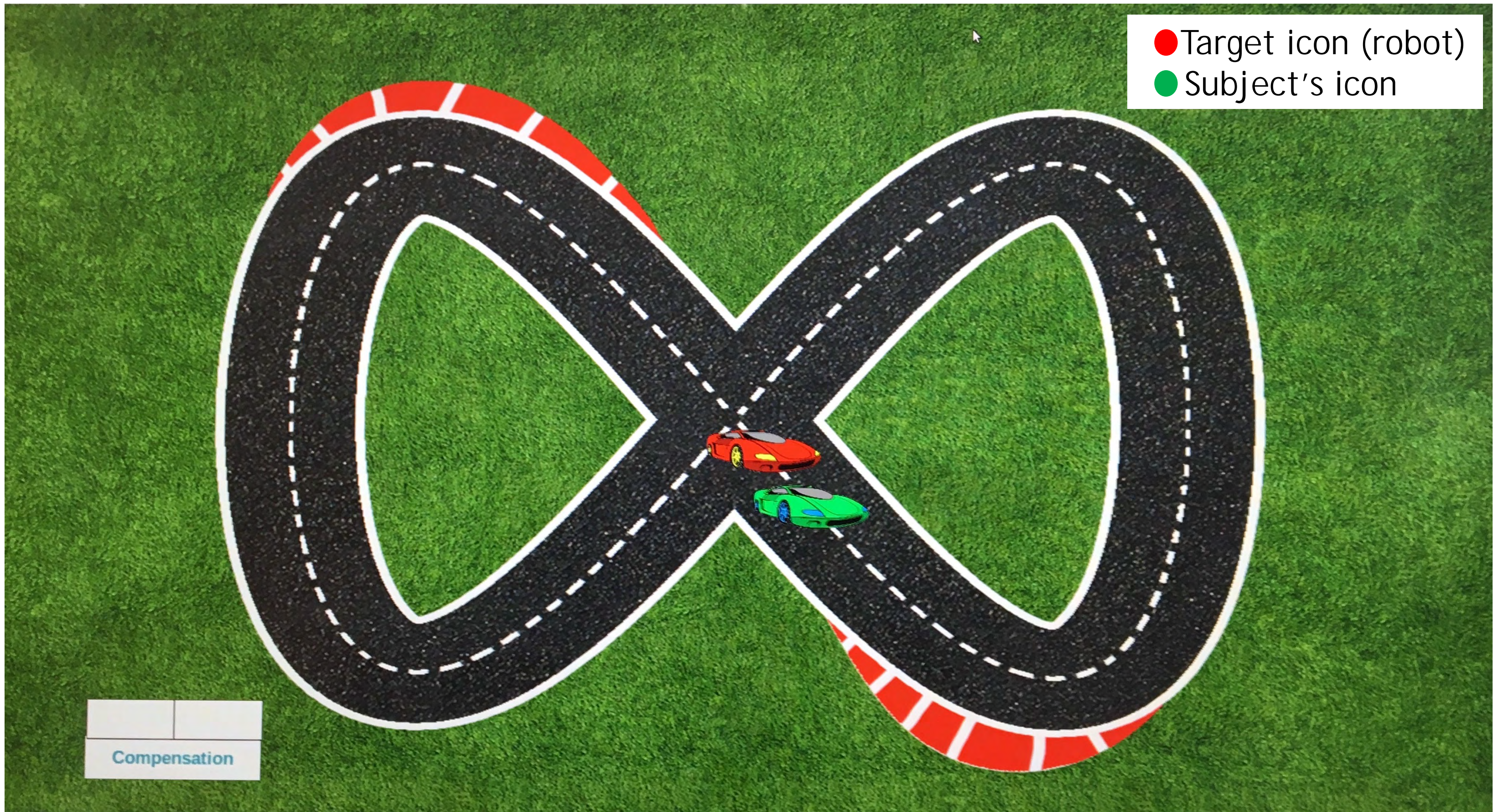


Figure 2. Tracking task performed during training sessions. Modulation of assistance was updated in real-time during the training to aid the participant (assistance or resistance to challenge the participant)

Assistance/Resistance

- Adaptive protocol based on online modulation of the assistance during the tracking task (Figure 2)
- When modulation was:

+ = ASSISTANCE - = RESISTANCE

Figural error was measured in degrees and computed as shown in the following equations

$$distAB_i = \min_j |A_i - B_j| \quad i=1,2,...,n$$

$$distBA_j = \min_i |A_i - B_j| \quad j=1,2,...,m$$

$$FE = \frac{i=1 \dots n distAB_i + j=1 \dots m distBA_j}{n+m}$$

Modulation was adjusted for the following 3 laps as a computation of the mean figural error and the assistance level or the previous laps:

$$modulation_{new} = modulation_{old} + a * (FE_{last3} - FE_{old}) + b$$

Results

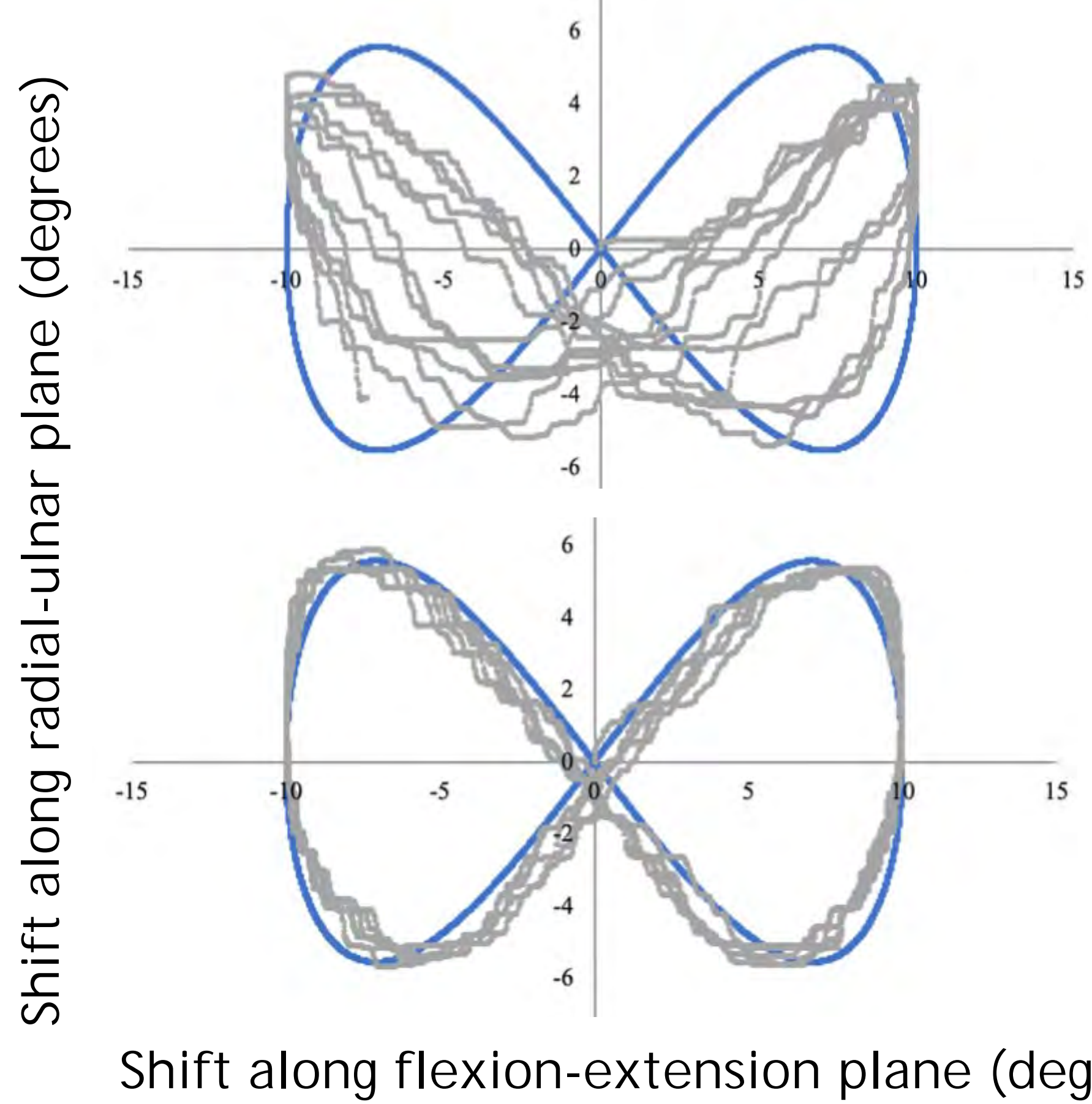


Figure 3. Figural error displayed at assessment Time 1 (top) vs. Time 2 (bottom). Blue line represents target trajectory, and the grey line represents the participant's trace

Discussion

- Tracking and figural error in the trained limb improved significantly ($p = 0.03$) for each participant (sample, Figure 3)
- Mean isometric wrist strength for the trained limb significantly ($p = 0.03$) increased from pre- to post-intervention
- Although only the most affected limb underwent the adaptive training protocol, both limbs showed improvements

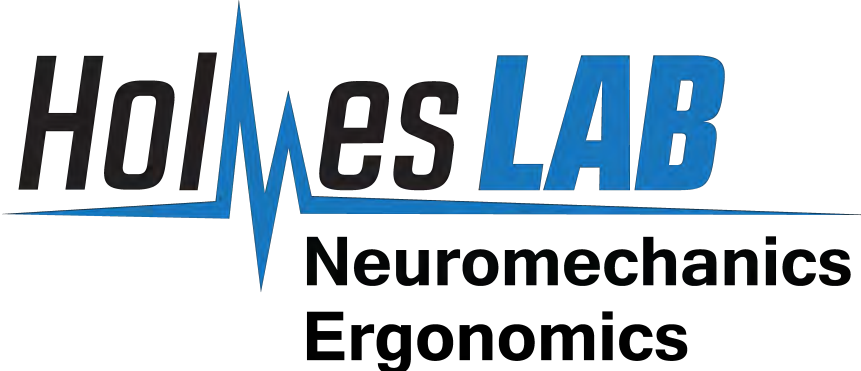
Conclusion

- Results provide a proof-of-concept that motor control and muscular strength can be improved by this type of rehabilitation
- The adaptive approach has demonstrated effective individuation of the therapy process for various types of MS, severity of disease and age levels

Funding Sources



ISTITUTO ITALIANO DI TECNOLOGIA



Type of submission: Scientific Poster

Neurovision: Visual Rehabilitation for Homonymous Hemianopsia

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Presenting author: Murie Fernandez, Manuel

Background and purpose: Visual problems following a brain damage are of high prevalence, with the most commonly reported issue being homonymous hemianopsia. This study tested the validity of the Neurovision visual rehabilitation and its efficacy in addressing damage to the visual field.

Methods: The Neurovision was validated by comparing the campimetries completed using Neurovision to those carried out with the Ophthalmology department in the local hospital. The results of both were compared using a logistic regression analysis. To study the effectiveness of the Neurovision rehabilitation activities in improving vision in patients with homonymous hemianopsia an interventional pre-post experimental study was carried out using 38 eyes from a cohort of 19 patients with stroke, traumatic brain injury and glioblastomas.

Results: The validation of the campimetry used in the Neurovision was shown to have similar results to that used in the Ophthalmology department, with a lineal regression of 0.72 (95% CI 0.66-0.79). The effectiveness of the Neurovision rehabilitation activities showed an overall significant improvement in total vision, with an average = 9.7(SD=10.9) ($p<0.001$). Significant improvements were also observed when analysing individual visual quadrants. The number of sessions was not found to be statistically significant, however when using a Spearman test there was an inverse relationship between time passed since injury and visual field recovery.

Conclusion: The portable Neurovision is capable of carrying out campimetries of similar quality of those performed by Ophthalmology departments. The results obtained in the pre and post experimental study also show that it is effective in improving the visual field of patients experiencing homonymous hemianopsia, therefore demonstrating its validity as a visual rehabilitation tool.

Keywords: Homonymous hemianopsia, visual field deficit, visual rehabilitation, stroke rehabilitation, stroke.

References:

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Effect of Brain Computer Interface Based Rehabilitation Combined With Action Observation and Peripheral Nerve Electrical Stimulation on Mu Suppression in Stroke Patients

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Stroke is a leading cause of long-term disability and is often associated with persistent impairment of the upper extremities[1]. Therefore, providing effective and efficient rehabilitation to restore upper limb function is important in patients with stroke[2]. Brain computer interface (BCI) is a promising technique to detect a user's intention and provide them with brain state-dependent feedback to assist rehabilitation. Peripheral electrical stimulation(PES) is a conventional method used to enhance rehabilitation outcome by promoting motor cortical activation[3]. In this study, we investigate the combined effects of BCI action observation (AO) feedback and PES on Mu suppression.

We developed a BCI-AO game in which a user can get feedback according to the degree of their watching AO. In this study, the grasping action contents was used so that users could see the change of "arm muscle" while their watching. Seventeen hemiplegic stroke patients and 17 healthy subjects were recruited in this study. All participants watched the grasping under four different tasks 1)AO; 2)AO+ES; 3)BCI AO+ES; 4)BCI AO+triggered ES (tES). The activation of mirror neuron system was examined with the amount of mu suppression during each condition.

We found a significant main effect between four tasks for Mu suppression in affected hemisphere in stroke patients ($F=4.33$, $p=.01$ in C3, $F=4.41$, $p=.01$ in F7). Post hoc multiple comparisons revealed that Mu suppression in stroke patients were significantly higher on C3 in AO vs. BCI AO+tES ($t=3.30$, $p=.01$) and on F7 in AO vs. BCI AO+ES ($t=3.07$, $p=.01$) in AO vs. BCI AO tES ($t=3.09$, $p=.01$).

These results support that the BCI AO feedback combined with PES is superior to AO or AO+PES for facilitating Mu suppression in affected hemispheres of patients with stroke. Therefore, we suggest that the BCI-AO feedback could be applicable and effective during AO or AO PES.

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Type of submission: Scientific Poster

Assessment of the Effects of Early Functional Proprioceptive Stimulations in Patients With Spinal Cord Injury

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Presenting author: Martinache, Florence

Spinal cord injury (SCI) is a dramatic event resulting in a long-term handicap. Appropriate care from admission to the intensive care unit (ICU) is a key element not only for the survival of these patients but also to promote their recovery. Moreover, the studies on natural history of SCI have shown that most of the recovery occurs within the first 3 to 6 months post-injury [1]. This period is therefore crucial for patients with SCI. However, the environment of the ICU and the acute condition of the patients limit the rehabilitation possibilities. In such a context, functional proprioceptive stimulations (Vibramoov system®, Techno Concept, France) could be a tool of interest. By using tendon vibrations, the Vibramoov system allows to reproduce the proprioceptive signatures of cyclic movements such as walking [2]. Some studies have already demonstrated the benefits of proprioceptive vibrations [3]. However, so far, these benefits have only been studied at the chronic stage of neurological diseases. We hypothesized that early functional proprioceptive stimulations (FPS) may reduce spasticity and promote sensorimotor recovery in tetraplegic and high paraplegic patients. To test our hypothesis, we conduct a randomized controlled trial on 40 patients with traumatic SCI. These patients will be stratified into two groups according to the completeness of their lesion. Every patient will be included within ten days post-injury and receive either FPS, either sham stimulations to the joints of the lower limbs, 4 times a week during 8 weeks. Our primary outcome measures assess spasticity. We also assess sensorimotor recovery, pain, muscle wasting and cognitive impairment. We record spasticity measurements at baseline, every two weeks during the 8 weeks of treatment and then at 6 months and 1 year post-injury. This study will help to specify the interest of such an early and intensive intervention on patients with SCI.

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Type of submission: Scientific Poster

Effects of Transcutaneous Spinal Cord Stimulation on Sensorimotor Circuitry and Cervico-Lumbar Coupling in Neurologically Intact Participants

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Presenting author: Parhizi, Behdad

Impaired coupling between cervical and lumbar spinal networks after spinal cord injury (SCI) can be reengaged via arm and leg (A&L) cycling training. Sensorimotor circuitry including cervico-lumbar coupling may further be enhanced by non-invasive modulation of spinal circuitry using transcutaneous spinal cord stimulation (tSCS). Two studies aimed to determine the effect of cervical, lumbar, or combined tSCS on cervico-lumbar connectivity and corticospinal excitability during static and rhythmic arm and leg tasks. During study 1 (n=13), Hoffman (H)-reflexes were elicited in the soleus muscle (SOL), while in study 2 (n=14), the amplitude of H-reflexes and motor evoked potentials (MEPs) were evaluated in the flexor carpi radialis muscle (FCR). These were assessed during 2 tasks: 1) Static; 2) Rhythmic cycling of the arms (study 1) or legs (study 2). In both studies, conditions included 1) No tSCS; 2) cervical tSCS; 3) lumbar tSCS. Study 2 also included combined cervical and lumbar tSCS. As expected from previous studies (de Ruyter et al., 2010), SOL H-reflex amplitude was suppressed by 19% during arm cycling relative to arms static (without tSCS). Interestingly, a similar reduction in the amplitude of the SOL H-reflex (by 23%) was induced by cervical tSCS while the arms were held static. Leg cycling suppressed the FCR H-reflex by 14%, but in contrast to the effect of cervical tSCS on the SOL H-reflex while the arms were static, Lumbar tSCS facilitated the FCR H-reflex amplitude by 11% when the legs were static. Combining cervical and lumbar tSCS facilitated FCR H-reflex and MEP amplitude by 20% compared to static No-tSCS. H-reflexes and MEPs were unaltered by tSCS during arm or leg cycling. These observations help to elucidate contributing mechanisms involved in the use of tSCS which may facilitate its targeted use to reengage previously inaccessible circuitry to enhance interlimb coupling and improve motor function after SCI.

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Type of submission: Scientific Poster

Electrode Number Alters the Relationship Between the Stimulation Frequency of Functional Electrical Stimulation and Quadriceps Torque in Individuals Who Are Neurologically Intact or Living With a Spinal Cord Injury

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During functional electrical stimulation (FES), rotating pulses between multiple electrodes reduces fatigability by delivering pulses to each active electrode at relatively low frequencies which maintains low motor unit (MU) discharge rates, while the “net” frequency can produce large, fused, contractions (1,2). Here we assess whether increasing the number of electrodes increases torque produced by the quadriceps at higher frequencies of stimulation in individuals who are neurologically intact (n=15, study A) or living with motor complete spinal cord injury (n=18, study B). In study A, 4 sessions were completed during which FES was delivered through 1 (FES1), 2 (FES2), 4 (FES4) or 8 (FES8) active electrodes. For each configuration, FES was initially delivered to produce 20% of a maximum voluntary contraction at 40 Hz. Torque-frequency relationships and discomfort were characterized across 6 frequencies from 20-120 Hz. In study B, 4 FES sessions delivered either FES1 or FES4 (similar to study A), through an active electrode over the femoral nerve (‘nFES’), or with pulses being alternated between the muscle and nerve sites (interleaved FES, ‘iFES’). Torque-frequency relationships were characterized across 6 frequencies from 10-100 Hz for each configuration. In study A, as frequency increased from 20-120 Hz, torque increased by 7, 13, 21 and 24% MVC, for FES1, 2, 4 and 8, respectively, while FES4 and FES8 evoked more torque than FES1 and FES2 at frequencies above 40 Hz. In study B, as frequency increased from 10-100 Hz, force increased by 18, 13, 25 and 32 N for FES1, nFES, iFES and FES4, respectively, and at 100 Hz, FES4 generated more force than all other configurations. Increasing channel number provides a unique opportunity to increase contraction amplitude while minimizing fatigability by generating contractions that increase in force as net stimulation frequency is increased, while individual MUs are recruited within their physiological firing range.

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Vibratory Alerts to Counter Developmental Disregard in Children With Unilateral Cerebral Palsy: A Feasibility Study

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Presenting author: Flamand, Véronique

Rationale: Children with unilateral cerebral palsy often struggle with developmental disregard; they neglect their more affected upper extremity, partly because of sensory and perceptual deficits. In adults with stroke, promising technology such as bracelets/watches providing repeated vibratory stimulations have been shown to enhance the use of the affected upper extremity in daily life. Despite the potential of this technology, few studies have explored its use in children with cerebral palsy.

Objectives: The aims of this study are to evaluate the acceptability of intensively wearing a watch providing vibratory feedback, and its influence on bimanual and occupational performance of children with unilateral cerebral palsy.

Method: This feasibility study will include five children aged 8 to 14 years old with unilateral cerebral palsy. Participants will wear a watch providing vibratory feedback when the more affected upper extremity is inactive for 60 seconds, over seven consecutive days. The amount of movement (inertial sensors), bimanual (at-home videotaped bimanual assessment) and occupational performance (Canadian Occupational Performance Measure) will be measured pre and post. The Quebec User Evaluation of Satisfaction with assistive Technology will measure acceptability.

Results and Practice Implications: Data collection and analyses are ongoing. The use of the vibratory watch could be recommended by occupational therapists to children with developmental disregard as a complement to conventional approaches.

Conclusion: After intensive use of the watch, the vibratory feedback might help to increase the use of the more affected upper extremity in daily life.

References:

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Interactive technologies of engineering in rehabilitation (INTER)

Type of submission: Scientific Poster

Adhesive Capsulitis: What If Robotics Rehabilitation Can Be Used for Management?

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Introduction and aims

Adhesive capsulitis is characterized by pain and decreased range of motion, therefore is responsible for a functional limitation and a cortical reorganization, which leads to disability and alteration in the quality of life. As the pathophysiology is not clearly understood, there is no consensus to date, on its management.

In an era of new technologies, robotics and virtual reality have shown great interest in functional rehabilitation and cortical reorganization, especially in neurorehabilitation.

The aim of our study is to assess the interest of robotic rehabilitation in adhesive capsulitis treatment.

Methods

It's a single-blinded randomized controlled trial which is including 40 patients with idiopathic adhesive capsulitis.

They are randomized into two groups:

- An intervention group is assigned to 12 sessions of Armeo@Spring, 12 sessions of continuous passive motion (CPM) and home exercise program.
- A control group is receiving conventional therapy.

Results

So far, 12 patients were included from March 23rd, 2021. The measured outcomes are the Shoulder Pain and Disability Index (SPADI), Range of motion, pain (EVA) and quality of life questionnaire SF-36, measured at baseline, 3weeks, 6 weeks and 3,6, 9 and 12 months of intervention.

Conclusion

In the term of our study, we should be able to focus on the role of robotics and virtual reality in adhesive capsulitis management.

Key words: adhesive capsulitis, robotics, virtual reality

References:

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Adhesive Capsulitis: what if robotics rehabilitation can be used for management ?

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Introduction

Adhesive Capsulitis is a condition characterized by pain and stiffness of the shoulder joint. It causes a three planes limitation of active and passive range of motion (ROM)(1). Its evolution leads to a cortical reorganization and functional limitation with a negative impact on the quality of life. Adhesive Capsulitis prevalence ranges between 2% to 5% for the general population, in particular women aged between 40 and 60 years old (2). Although it may take between 12 to 30 months, the condition generally gets better over time (3). Meanwhile, patients keep experiencing functional limitation and worst psychological and social burden.

The treatment is intended to decrease pain and to raise ROM; and therefore, enhance shoulder function. The therapeutic protocol includes prescribing analgesics or anti-inflammatory drugs (4,5) with passive and active mobilizations to fight stiffness and to increase functional capacities (6,7). Task-oriented rehabilitation focuses on performing daily life activities. Rehabilitation can involve the use of a technological aid such as a robotic splint and virtual reality.

The aim of this study is to evaluate the efficiency of using an exoskeleton connected to virtual reality software for Adhesive Capsulitis 'rehabilitation to decrease shoulder pain and disability.

Materials

In our study, we used an ergonomic upper limb exoskeleton that combines robotic assistance and virtual reality: The Armeo®Spring, Hocoma, Switzerland.

Features:

- This robotic rehabilitation device has seven axes (8) and allows virtual gaming in an extensive three-dimension (3D) workspace,
- It is adjustable so that the exoskeleton aligns with the upper limb. The exoskeleton is attached to a trolley with head support allowing individual adjustments. The patients'arm can be attached to the exoskeleton by Velcro belts,
- It has both an arm weight and a lower forearm support. The gravity compensation system can be adjustable by nine settings in the arm and the forearm (9), which improves the movement of the affected arm / in this case, range of motion and shoulder function,
- It's connected to a software that provides self-directed and virtual exercises supported by visual and sound feedback,
- It allowed the therapist to modify all exercise parameters such as duration, intensity, and type of feedback.

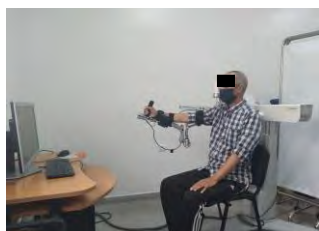


Figure 1: Armeo®Spring, Hocoma, Switzerland

Methods

Study design: It's an ongoing randomized controlled trial, which is conducted at the Physical Medicine and Rehabilitation Unit at University Hospital of Rabat. This is a prospective comparative analytic trial which aims to assess the benefit of functional rehabilitation using robotic, passive mobilization and self-program exercises in the treatment of Adhesive Capsulitis.

Written informed consent was obtained from all patients. All procedures are conformed to the Declaration of Helsinki and were approved by the institutional human research ethics committee.

Inclusion criteria: Patients over 18 years old, pain and / or limitation of range of motion of the shoulder joint, idiopathic Adhesive Capsulitis or Adhesive Capsulitis associated with confirmed systemic disease.

Exclusion criteria: Cognitive disorders, history of surgery, shoulder fracture or dislocation, shoulder tendinopathy, history of inflammatory, degenerative or infectious disease, history of neurological disease (Parkinson's disease, stroke, multiple sclerosis, and radiculopathy), treatment during the previous 6 months: hyaluronic acid infiltration, hydro dilatation, manipulation under anesthesia, surgical capsular release.

However, level I and level II analgesics, non-steroidal anti-inflammatory drugs (NSAIDs), and corticosteroid infiltration, are allowed during the previous 6 months and during the intervention.

Randomization: Participants are randomized by a computer-generated list handed over by the statistic laboratory of Faculty of Medicine and Pharmacy in Rabat.

- The intervention group** is receiving 12 sessions of passive mobilization on continuous passive motion (CPM) followed by 12 sessions of robotic therapy sessions using the Armeo®Spring; each includes 4 exercises of 10 minutes each. A standardized program has been pre-established aiming to work with maximum lightening, then gradually, enlarge the workspace and reduce the arm support system. Also, the candidates are given a program guide for home exercises.
- the control group** is receiving a standard 4-item rehabilitation prescription: analgesic physiotherapy, passive mobilization, functional work and learning a self-program by a physiotherapist of their choice.

Sample size: We calculated a sample size of 20 subjects per group with a power of 90%, alpha 0.05 and a 10% drop out rate.

Outcomes:

The primary outcome is measured by the Shoulder Pain and Disability Index (SPADI). It is a self-administered questionnaire made of two sections: the first section includes 5 questions that assess the patient's pain; the second section uses 8 questions to assess patient limitations performing daily living activity that require shoulder use. The rating of each item ranges from 0 to 10 points; the average of the scores represent the SPADI score which can range from 0 to 100 - a high score indicates a significant disability. We will use the validated Arabic version (10). The secondary outcomes are the pain evaluated by the Visual Analogic Scale a (VAS), the active and passive range of motion measured by a goniometer and the quality of life measured by the SF-36 quality of life index. All data are collected by the investigator at clinical baseline and the follow-up at the 3rd and the 6th week, then at the 3rd, the 6th, the 9th and at the 12th month of the intervention.

Results

Recruitment began on March 23, 2021, until now, 22 patients were selected, only 13 were included. 84.6% (n = 11) were women, with a median age of 55 years (Table 1). 53.8% (n = 7) had Adhesive Capsulitis on the right shoulder and 53.8% (n = 7) had a history of diabetes.

Table 1: Population's age

	age
N	13
Missing	0
Median	55
Shapiro-Wilk W	0.852
Shapiro-Wilk p	0.030
25th percentile	50.0
75th percentile	68.0

Table 2: Paired Samples T-Test

							95% Confidence Interval	
		statistic	Df	p	Mean difference	SE difference	Lower	Upper
SPADI pain at baseline	SPADI pain at 6FWF	1.923	5.00	0.113	14.33	7.46	-4.83	33.50
SPADI disability at baseline	SPADI disability at 6FWF	3.248	5.00	0.023	21.21	6.53	4.43	37.99
SPADI total at baseline	SPADI total at 6FWF	3.181	5.00	0.025	19.92	6.26	3.82	36.02
EVA at baseline	EVA at 6FWF	5.697	5.00	0.002	60.83	10.68	33.38	88.28
Active abduction at baseline	Active abduction at 6FWF	-4.406	5.00	0.007	-41.67	9.46	-65.98	-17.36
Active flexion at baseline	Active flexion at 6FWF	-5.477	5.00	0.003	-50.00	9.13	-73.47	-26.53
Active external rotation at baseline	Active external rotation at 6FWF	-2.928	5.00	0.033	-10.00	3.42	-18.78	-1.22
Passive abduction at baseline	Passive abduction at 6FWF	-4.577	5.00	0.006	-45.00	9.83	-70.27	-19.73
Passive flexion at baseline	Passive flexion at 6FWF	-5.078	5.00	0.004	-46.67	9.19	-70.29	-23.04
Passive external rotation at baseline	Passive external rotation at 6FWF	-2.892	5.00	0.034	-10.83	3.75	-20.46	-1.21
SF-36 at baseline	SF-36 at 6FWF	0.256	4.00	0.810	1.40	5.46	-13.77	16.57

Table 3: Repeated measures ANOVA

	Sum of squares	df	Mean square	F	p
SPADI pain	1157	2	578	4.27	0.040
SPADI disability	923	2	462	4.18	0.042
SPADI total	1137	2	569	5.47	0.021
EVA	13531	2	6765	17.8	<.001
Active abduction	4831	2	2415	8.60	0.005
Active flexion	7031	2	3515	15.7	<.001
Active external rotation	402	2	201.2	5.83	0.017
Passive abduction	6029	2	3014	10.1	0.003
Passive flexion	7102	2	3551	23.1	<.001
Passive external rotation	407	2	203.6	8.84	0.004
SF-36	21.4	2	10.7	0.280	0.761

Statistical analysis was performed by Jamovi 1.6.23 software. Preliminary results by comparing measured outcomes at baseline and 6 weeks are shown in table 2. Continuous variables were analyzed using the paired t-test among groups (Table 2) and repeated measure ANOVA within the interventional group (Table 3).

Discussion

Adhesive Capsulitis is manifested by a painful reduction in joint range of motion which causes the underuse of the affected limb, thus, a restriction of daily living activities.

- The Armeo®Spring, Hocoma, is a medically certified robotic rehabilitation device. Initially used in the neurorehabilitation field, a German team have used it in the rehabilitation of humeral fractures in a multicenter intervention trial (11). This ergonomic exoskeleton of upper limb has a gravity support system that allows mechanical assistance of the movements which makes it easier for patients. By doing supported active exercise, patients can progress and increase ROM painlessly and gradually.
- Patients with shoulder pain tend to underuse the affected limb. The pain is responsible for cortical mechanisms (12). Indeed, there is a close relationship between the perception of space and body schema (13). So, by not using the affected limb, patients are unlikely neglecting the painful shoulder. The Armeo®Spring, Hocoma puts forward to a cortical reorganization, based on the principle of motor learning. In this regard, repetition and active participation are fundamental contributors.
- Studies in rehabilitation shows that virtual world practice promotes active participation during the exercise. The software connected to the exoskeleton allows to facilitate the interactive work through a virtual environment. The training is based on task-oriented exercises which contribute to improve the limb function. Along with it, multimodal feedback implemented in the training increase engagement and motivation for working and so recovery (4). Hence, robot-assisted training is a new modality that can provide more effective rehabilitation.
- Regarding the preliminary results of our study, the primary outcome, SPADI total score was statistically significant. However, The SPADI pain was not statistically significant, maybe because patients were having active-sessions training in the Armeo®Spring, Hocoma during the 3 weeks prior to follow-up.
- Active and passive ROM was statistically significantly improved in all movement (p<0.03), although the SF-36 questionnaire was not because it's premature given the natural history of Adhesive Capsulitis.

Considering it's an ongoing study, the main bias is the small sample size. Furthermore, we are barely at 6 weeks of follow-up. In the term of our study, we should be able to focus on the role of robotics and virtual reality in Adhesive Capsulitis management.

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Type of submission: Scientific Poster

Brain-Computer Interface System for Gait Rehabilitation of Chronic Stroke Patients

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Presenting author: Sebastián-Romagosa, Marc

Background

Neurorehabilitation based on Brain-Computer Interfaces (BCIs) show important rehabilitation effects for patients after stroke. Previous studies have shown improvements for patients that are in a chronic stage and/or have severe hemiparesis and are particularly challenging for conventional rehabilitation techniques.

Method

Seven stroke patients in chronic phase with lower extremity hemiparesis were recruited. All of them participated in 25 BCI-sessions about 3 times/week. The BCI-system was based on the Motor Imagery (MI) of the paretic-ankle dorsiflexion and healthy-wrist dorsiflexion with Functional Electrical Stimulation (FES) and avatar feedback. Assessments were conducted to assess the changes before and after the therapy. The functional scales used were: 10-meters walking test (10MWT), Range of Motion (ROM) of the ankle-dorsiflexion and Timed Up and Go (TUG).

Result(s)

Results show a significant increase in the gait speed in the primary measure 10MWT self-velocity of 0.14 m/s (SD = 0.10). This improvement is above of the minimally clinically important difference. The speed in the TUG also significantly increased by 0.08 m/s, $P = 0.016$. The range of motion also was increased after the therapy, $\Delta\text{ROM passive} = 8.83^\circ$ (SD = 7.22), $P = 0.016$, and $\Delta\text{ROM active} = 7.14^\circ$ (SD = 4.84), $P = 0.016$.

Conclusion(s)

These outcomes show the feasibility of this BCI approach, and further support the growing consensus that these types of tools might develop into a new paradigm for gait rehabilitation tool for stroke patients. However, the results are from seven chronic stroke patients so the authors believe that this approach should be further validated in broader studies involving more patients.

References:

This work was supported by:

Type of submission: Scientific Poster

Study Protocol of a Clinical Investigation on Safety, Feasibility and Usability of the ABLE Exoskeleton Device With Spinal Cord Injured Patients in a Hospital Setting

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We describe the main protocol features of an ongoing clinical study together with its unique aspects of implementation. This study aims to assess the safety, feasibility and usability of the novel ABLE exoskeleton in patients with spinal cord injury (SCI) during a 4-6 week in-patient training program as pre-evaluation for its home use. Although the clinical investigation is conducted according to the European Medical Device Regulation, the regulatory approval process at the two SCI centers (Barcelona (ES), Heidelberg (D)) differs substantially.

Primary endpoints are the number of (severe) adverse events and device-related drop-outs. Feasibility and usability are assessed by basic gait metrics and the Level of Assistance (LoA) (proprietary 5-level scale) for donning/doffing and completion of 4 activity tasks. The predefined activity tasks were implemented to achieve a better interindividual comparability. Secondary endpoints are walking tests and patient reported outcomes. Patients with traumatic as well as non-traumatic SCI representing a growing group of potential exoskeleton users [1] are included up to an age of 70 years. Due to the insufficient characterization of the functional impairment by the ASIA Impairment Scale, the inclusion criterion of sufficient arm strength was used instead. Furthermore, patients have to be able to perform a sit-to-stand transfer or to stand in the device with assistance in a screening session.

The exclusion criteria correspond to those of other SCI locomotion studies. Instead of using bone density measurements, patients are excluded if they show 5 or more clinical risk factors for fragility [2].

After screening, a baseline visit and 12 exoskeleton sessions are completed, followed by a post-training visit. Four weeks after the final training session a follow-up visit is performed by phone interview due to the current COVID-19 situation.

From 01.11.2020 to 31.07.2021, 21 patients were included. The study will finish in November 2021.

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Effects of Community-Based Ambulation Training With 3D-Printed Ankle-Foot-Orthoses on Walking on Even/Uneven Surfaces in Patients With Chronic Stroke

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Presenting author: Cho, Ji-Eun

Background: Community ambulation, e.g. stair or slope ambulation, is an important skill for stroke survivors whose walking ability and ankle function has been affected.¹ 3D-printed ankle-foot-orthoses(3D-AFOs) can be optimized to individual biomechanical requirements in stroke survivors to provide improved function, better fit and enhanced aesthetics.²

Objective: to determine the effects of community-based ambulation training with customized 3D-AFOs on gait and quality of life.

Material and Methods: Two stroke patients with chronic post-hemiparesis(F/M:0/2, age: 30/58 years, onset duration: 10/24 months, paretic side: Lt/Lt) participated in this study. Subjects participated in 20 community-based ambulation training sessions on four different environments, i.e. even, uneven surfaces, slope, and stair with increasing difficulties.³ To evaluate gait kinematics, the primary outcome, subjects repeated walking trial at least three times in a 10m on even and uneven surfaces at a self-selected speed. Secondary outcomes include balance and quality of life assessments.

Results: Subjects showed improvements in the walking performance over even surface (pre/post/follow-up of walking speed: 6.1/14.6/14.7cm/sec, paretic step length: 0.01/17.5/22.7cm, step time: 1.2/1.5/1.7sec) and uneven surface (step width: 15.0/17.6/19.6cm and paretic step length: -3.6/-2.4/22.7cm). In clinical assessments, pre-post results exhibited improvements in 6-minute walk test, Berg balance scale, Fugl-Meyer, stroke impact scale, and Beck-depression inventory.

Conclusion: The results suggest that community-based ambulation training with 3D-AFOs is effective on gait, balance, and quality of life. Further studies are recommended to study AFOs suitable for community ambulation according to individual levels.

Acknowledgements: Translational Research Center for Rehabilitation Robots, Korea National Rehabilitation Center, Ministry of Health & Welfare, Korea(#NRCTR-IN21003).

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Type of submission: Scientific Poster

Monitoring Patient Progress During Upper Limb Exoskeleton-Assisted Stroke Rehabilitation: Analysis of Built-in Data

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The efficacy of upper limb Robot-assisted Therapy (uIRT) is well established in the literature [1]. Biomechanical data registered by robotic devices have been employed for patient assessment [2], but rarely for monitoring the time course of motor recovery [3].

We present an assessment protocol (included into a multicentre RCT) for the objective analysis of patient performance during uIRT. The procedure is based on built-in data acquired by the Armeo®Power (HocomaAG, CH) and can be easily integrated into clinical practice as it does not require additional technology and specialized technical personnel.

At the 1st session of uIRT, a recursive procedure allows to tailor the amount of robotic support provided to the patient: with the optimum support level (starting from 30% and increasing with 10% steps) the patient is able to maintain for at least 30 seconds the upper limb in 45-degree shoulder flexion, the exoskeleton as close to the body as possible, and the forearm parallel to the ground. The support level set during the 1st session of uIRT will be used in the subsequent assessments (at 1st, 10th, and 20th sessions). Specifically, the following data will be gathered by the exoskeleton: the passive and active range of motion for each joint and movement; the passive and active workplace (i.e. the maximum volume reached by the hand); the maximum torque values for each joint during a single isometric muscle contraction; and the anatomical joint angles and the 3D joint trajectories during the execution of point-to-point reaching movements in different directions. An off-line processing of the built-in trajectories allows to calculate kinematic features (movement path error, mean movement speed, smoothness) which are representative of motor control [2].

The effectiveness of the built-in data in detecting patient progress is evaluated on subacute stroke patients. The results show that these measures are able to capture the patient progress over the course of uIRT.

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This work was supported by:

Hocoma AG (CH), Ministry of Health (Ricerca Corrente)

Monitoring Patient Progress during Upper Limb Exoskeleton-assisted Stroke Rehabilitation: Analysis of Built-in Data

Goffredo Michela, Pournajaf Sanaz, Franceschini Marco, on behalf of Italian PowerUPS-REHAB Study Group*

Neurorehabilitation Research Laboratory, Department of Neurological and Rehabilitation Sciences, IRCCS San Raffaele Roma, Rome, Italy

INTRODUCTION:

- The efficacy of upper limb Robot-assisted Therapy (uLRT) is well established in the literature [Mehrholz *et al.* 2018].
- Biomechanical data registered by robotic devices have been employed for patient assessment [Do Tran *et al.* 2018], but rarely for monitoring the time course of motor recovery [Goffredo *et al.* 2018].

AIM: objective analysis of patient performance during uLRT based on built-in data acquired by the Armeo®Power exoskeleton (HocomaAG, CH).



Armeo®Power exoskeleton
(HocomaAG, CH)



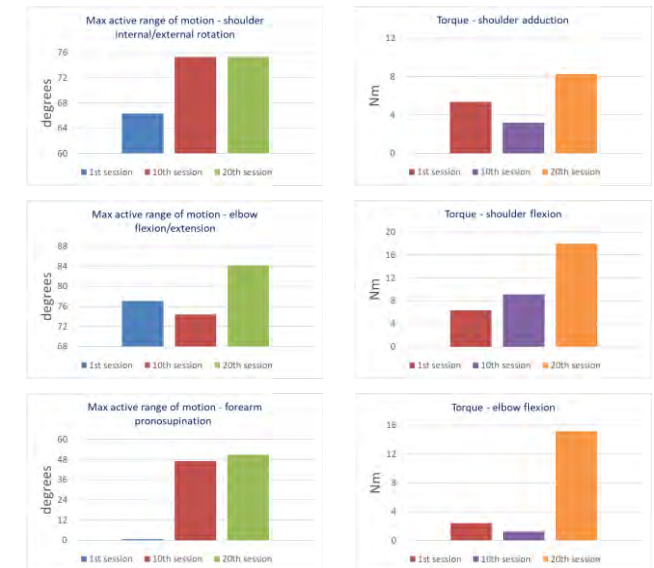
* Italian PowerUPS-REHAB
Study Group ClinicalTrials.gov
Identifier: NCT04697368

METHODS:

- At the 1st session of uLRT, a recursive procedure allows to tailor the amount of robotic support provided to the patient: with the optimum support level (starting from 30% and increasing with 10% steps) the patient is able to maintain for at least 30 seconds the upper limb in 45-degree shoulder flexion, the exoskeleton as close to the body as possible, and the forearm parallel to the ground.
- The following data will be gathered by the exoskeleton at 1st, 10th, and 20th sessions:
 1. the passive and active range of motion for each joint and movement;
 2. the passive and active workplace (i.e. the maximum volume reached by the hand);
 3. the maximum torque values for each joint during a single isometric muscle contraction;
 4. the anatomical joint angles and the 3D joint trajectories during the execution of point-to-point reaching movements in different directions.
- An off-line processing of the built-in trajectories will allow to calculate kinematic features (movement path error, mean movement speed, smoothness) which are representative of motor control [Do Tran *et al.* 2018].

RESULTS & CONCLUSIONS:

- The effectiveness has been evaluated on subacute stroke patients.
- These measures are able to capture the patient progress over the course of uLRT.



- The assessment protocol can be easily integrated into clinical practice: it does not require additional technology and specialized personnel.

Type of submission: Scientific Poster

Clinical and Neurophysiologic Effects of Upper Limb Robot-Assisted Rehabilitation on Motor Recovery in Patients With Subacute Stroke: A Study Protocol of a Single-blind Multicenter Randomized Controlled Trial

Pournajaf, Sanaz¹; Goffredo, Michela¹; Franceschini, Marco^{1,2}; On behalf of Italian PowerUPS-REHAB Study Group³.

1: Neurorehabilitation Research Laboratory, Department of Neurological and Rehabilitation Sciences, IRCCS San Raffaele Roma, Rome, Italy; 2: Department of Human Sciences and Promotion of the Quality of Life, San Raffaele University, Rome, Italy; 3: clinicalregistration.gov Identifier: NCT04697368.

Presenting author: Pournajaf, Sanaz

The promising effects of Upper Limb (UL) Robot-Assisted Therapy (RAT) has been proven by literature[1] and its use in clinical routine is escalating. Task-specific, high intensity and repetitive exercises are defined as key points to facilitate motor re-learning in neurorehabilitation[2], as RAT can provide with an assisted-as-needed approach[3].

This RCT's aims are: i) investigating the clinical effects of an exoskeleton robotic system for the UL rehabilitation compared to Conventional Therapy (CT) in subacute stroke subjects; ii) identifying patients' characteristics (Distance Since Stroke Onset (DSO); UL impairment predicting a better recovery after UL-RAT; iii) detecting whether the UL-RT could elicit a greater brain stimulation.

84 subjects, in 8 rehabilitation centers, after first-ever cerebral stroke with severe or moderate hemiparesis; sufficient cognitive and stable clinical conditions will be recruited, and randomly assigned into Experimental Group-EG receiving UL-RAT through Armeo®Power exoskeleton (Hocoma AG, CH) for 25 sessions-5 days/week—45minutes each; or Control Group-CG receiving CT, in addition to the regular rehabilitation program. A sample stratification based on DSO ($DSO \leq 30$; $DSO > 30$) and Fugl-Meyer Assessment (FM)-UL ($FM-UL \leq 22$; $22 < FM-UL \leq 44$) will be considered for the randomization. All participants will be assessed clinically at baseline (T0), at the end of the treatment (T1), and at 6 months follow-up (T2). The motor evaluation part of FM-UL (0-66) is considered as the primary outcome. Clinical assessments are set based on International Classification of Function, Disability and Health (ICF). A patients' satisfaction questionnaire will be evaluated in EG at T1. A sub-group of patients (N=30) will be evaluated at T0 and T1 via Electroencephalography. Brain electrical activity will be recorded during rest conditions with closed and open eyes (5 minutes each). Preliminary results on first 10 patients sustained the hypothesis of the study.

References:

- Mehrholz J, Pohl M, Platz T, Kugler J, Elsner B. Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke. Cochrane Database Syst Rev. 2018 Sep 3;9(9):CD006876. doi: 10.1002/14651858.CD006876.pub5. PMID: 30175845; PMCID: PMC6513114.
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This work was supported by:

Hocoma AG, CH 1, Italian Ministry of Health-Ricerca Corrente 2.

CLINICAL and NEUROPHYSIOLOGICAL EFFECTS of UPPER LIMB ROBOT-ASSISTED REHABILITATION on MOTOR RECOVERY in PATIENTS WITH SUBACUTE STROKE: a STUDY PROTOCOL of a SINGLE-BLIND RANDOMIZED CONTROLLED TRIAL

Pournajaf, Sanaz¹; Goffredo, Michela¹; Sofia Straudi²; Maria Rosaria Leo³; Serena Filoni⁴; Vincenzo Cimino⁵; Andrea Santamato⁶; Giovanni Morone⁷; Marco, Franceschini¹; On behalf of Italian **PowerUPS-REHAB Study Group**⁸.

1: Department of Neurological and Rehabilitation Sciences, IRCCS San Raffaele Roma, Rome; 2: AUSL Ferrara University Hospital, Ferrara; 3: Villa Bellombra Hospital, Bologna; 4: Fondazione Gli Angeli di Padre Pio, San Giovanni Rotondo; 5: IRCCS Centro Neurolesi Bonino Pulejo, Messina; 6: Ospedali Riuniti University Hospital, Foggia; 7: IRCCS Santa Lucia, Rome; 8: clinicalregistration.gov Identifier: NCT04697368, Italy

Introduction

The promising effects of Upper Limb (UL) Robot-Assisted Therapy (RAT) has been proven by literature [1] and its use in clinical routine is escalating. Task-specific, high intensity and repetitive exercises are defined as key points to facilitate motor re-learning in neurorehabilitation [2], as RAT can provide with an assisted-as-needed approach [3].

Multicenter RCT's Aims



Figure 1. Armeo@Power exoskeleton (Hocoma, Zurich)



Scan the QR-Code to see the robot video

- I. To investigate the **clinical effects** of an exoskeleton robotic system for the UL rehabilitation compared to Conventional Therapy (CT) in subacute stroke subjects;
- II. To identify **patients' characteristics** (e.g. Distance Since Stroke Onset (DSO), and UL impairment) **predicting a better recovery** following UL-RAT;
- III. To detect whether the **UL-RT** could elicit a **greater brain stimulation**

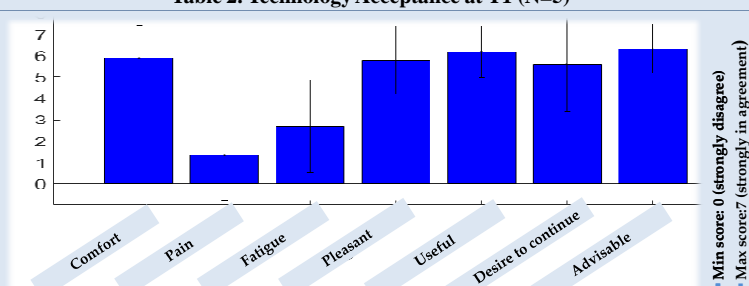
Expected Results

- ✓To identify a customizable rehabilitation protocol for upper limb motor recovery based on the clinical characteristics of patient;
- ✓To achieve better motor recovery both in terms of range of motion and muscle recruitment associated with cognitive stimulation following the UL rehabilitation through the Armeo Power exoskeleton system;
- ✓To classify clinical characteristics for the prediction of rehabilitation outcomes, in terms of motor recovery;
- ✓To achieve greater stimulation at the cortical level following the experimental treatment;
- ✓To achieve better muscle activation and therefore better motor performance in the EG;
- ✓To maintain the acquired rehabilitative effects also at the follow-up in the EG, thus obtaining greater autonomy in the performance of the ADL and a better participation.

Table 1. Sample's demographic and clinical characteristics data (N=10)

	EG (N=5)	CG (N=5)
Age (years)	56.5 ± 14	73 ± 6
Gender (female/male)	2 (40%)/3 (60%)	2 (40%)/3 (60%)
Etiology (ischemic/hemorrhagic)	4 (80%)/1 (20%)	4 (80%)/1 (20%)
Affected Side (left/right)	3 (60%)/2 (40%)	2 (40%)/3 (60%)
DSO (days)	49 ± 18	46 ± 22
UL Impairment (FM-UL motor evaluation)	18 ± 12	24 ± 11

Table 2. Technology Acceptance at T1 (N=5)



Discussion

Preliminary results on the first 10 patients (see Table1) sustained the hypothesis of the study. The UL-RT through Armeo@Power exoskeleton has been well accepted by patients in EG (Table 2). These results promote the feasibility of the study protocol and its application in the clinical routine. However, this study should be completed based on the calculated sample size, and integrated with instrumental data in order to draw reliable conclusions.

Conclusion

Study protocols on high number of subjects with similar clinical characteristics supported by various instrumental insights allow the scientific and clinical community to have clearer views on the use of innovative technologies available to rehabilitation.

This work was supported by: Hocoma, Inc., CH; Italian Ministry of Health (Ricerca Corrente).

Keywords: Stroke, Upper Limb Functions, Rehabilitation, Robot-Assisted Therapy, Neuroplasticity

References

- [1] Mehrholz J, et al. Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke. Cochrane Database Syst Rev. 2018 Sep 3;9(9):CD006876.
- [2] Tomassini V, et al. Structural and functional bases for individual differences in motor learning. Hum Brain Mapp. 2011 Mar;32(3):494-508.
- [3] Klamroth-Marganska V, et al. Three-dimensional, task-specific robot therapy of the arm after stroke: a multicentre, parallel-group randomised trial. Lancet Neurol. 2014 Feb;13(2):159-66.

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Type of submission: Scientific Poster

Motor Cortical Activation and Peripheral Blood Biomarkers in Progressive Multiple Sclerosis After a Robot-Assisted Gait Training: A Secondary Analysis of the RAGTIME Trial

Lamberti, Nicola ¹; Manfredini, Fabio^{1,2}; Crepaldi, Anna ¹; Baroni, Andrea ²; Secchiero, Paola ³; Pinton, Paolo ⁴; Bernardi, Francesco ⁵; Tisato, Veronica ³; Basaglia, Nino ^{1,2}; Straudi, Sofia ^{1,2}

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Presenting author: Straudi, Sofia

Background: This study aimed to determine cortical activation and peripheral blood biomarkers responses to Robot-assisted Gait Training (RAGT) compared with intensive Overground Walking (OW) in progressive multiple sclerosis (MS) [1,2].

Methods: We studied 24 MS patients (EDSS 6-7) enrolled in the RAGTIME trial to receive 12 sessions of RAGT (Lokomat) or intensive OW. Cortical activation during a treadmill walking task, assessed through fNIRS recordings from the motor and premotor cortexes (M1/PM), was calculated as the area under the curve (AUC) of oxyhemoglobin for each hemisphere and the total area (Tot-OxyAUC). Gait speed, endurance, balance and fatigue were also measured, along with five healthy control (HC) subjects. The measures were collected at baseline and after 4 weeks. A venous blood sample was also collected for the analysis of a panel of circulating biomarkers.

Results: At baseline, Tot-OxyAUC during walking was significantly increased in MS patients compared to HC and was significantly higher for those with more severe disabilities and higher BDNF concentration. After rehabilitation, significant opposite variations in Tot-OxyAUC were observed, with activity levels being increased after OW and decreased after RAGT ($p = 0.002$), particularly in patients who were trained at a lower speed. Greater reductions in the cortical activation of the more affected hemisphere were significantly related to improvements in gait speed ($r = 0.42$) and endurance ($r = 0.44$). In RAGT group only, the reduced cortical activation after rehabilitation was directly associated with a decrease in fatigue and in levels of inflammatory markers or an increase of neuro-regenerative ones.

Conclusions: Cortical activation, assessed through fNIRS, highlighted the brain activity in response to the type and intensity of rehabilitation. Moreover, after RAGT a modulation of proinflammatory and neuro-regenerative biomarkers was found.

References:

- Straudi et al. The effectiveness of Robot-Assisted Gait Training versus conventional therapy on mobility in severely disabled progressive Multiple sclerosis patients (RAGTIME): study protocol for a randomized controlled trial. *Trials*. 2017
- Straudi et al. Robot-assisted gait training is not superior to intensive overground walking in multiple sclerosis with severe disability (the RAGTIME study): A randomized controlled trial. *Mult Scler*. 2020.

This work was supported by:

This research was funded by a grant from the 2010–2012 Research Program of Emilia Romagna Region [grant number 1786/2012]

Motor Cortical Activation and Peripheral Blood Biomarkers in Progressive Multiple Sclerosis after a Robot-assisted Gait Training: A Secondary Analysis of the RAGTIME trial

Nicola Lamberti, Fabio Manfredini, Anna Crepaldi, Andrea Baroni, Paola Secchiero, Paolo Pinton, Francesco Bernardi, Veronica Tisato, Nino Basaglia, Sofia Straudi

Subjects and Methods

NCT02421731

24 PwMS (EDSS 6-7)



Overground Walking (n=12)

RAGT (Lokomat) (n=12)

12 sessions (4 weeks)

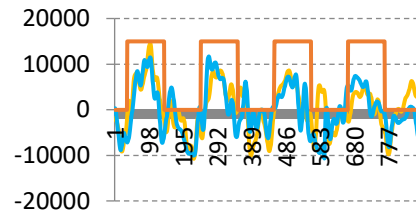
Outcomes:

Cortical activation (fNIRS)
Biomarkers (BDNF, Eotaxin)
Gait speed, 6MWD



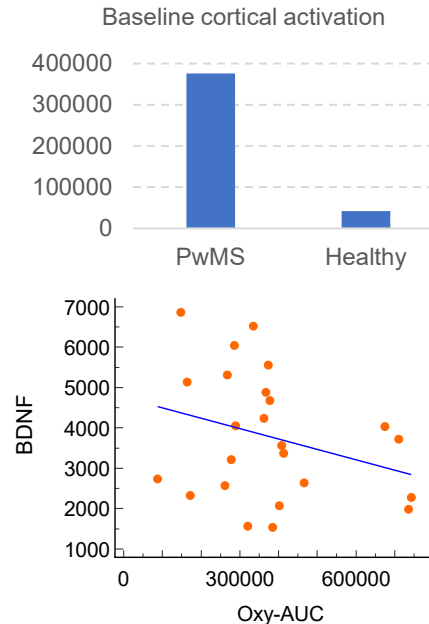
Cortical activation:

Area under-curve of OxyHb during a 0.2km/h walking task



Results

No baseline differences



Higher CA:

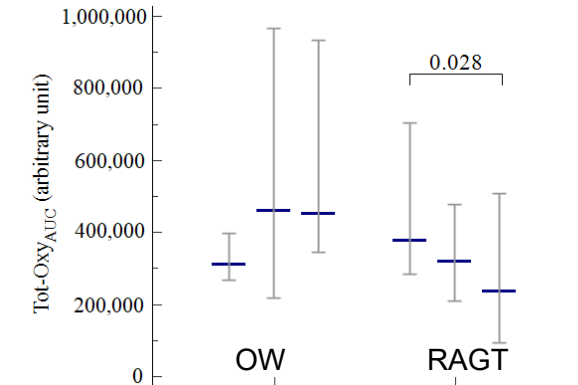
↑ EDSS

↓ gait speed, 6MWD

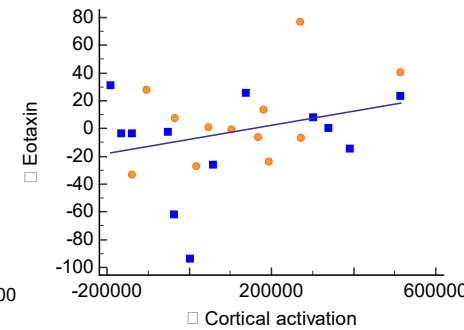
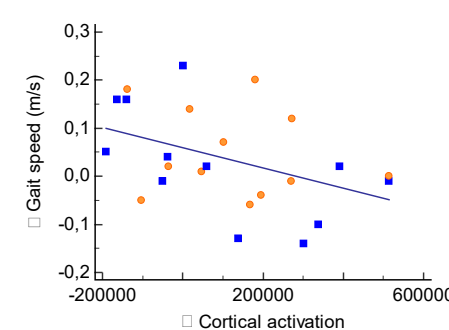
↑ inflammatory response

After rehabilitation

MCA significantly decreased after RAGT



Variations of MCA related with improvement of performance and anti-inflammatory activity



Conclusion: Different responses to rehabilitation in MCA were highlighted. A modulation of biomarkers particularly after RAGT was also observed.

Contact:

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Type of submission: Scientific Poster

Facial Therapy: A Remote Biofeedback System for Patients With Sequels of Peripheral Facial Paralysis

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2: Aldawa Technologies, Puebla, Mexico

3: Tecnológico de Monterrey, Tampico, Mexico

4: Universidad de las Américas, Puebla, Mexico

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Presenting author: Sucar, Luis Enrique

Peripheral facial palsy (PFP) is a cranial mononeuropathy that affects 30/100,000 persons. PFP is associated with weakness of the facial nerve, resulting in drooping of the brow, incomplete lid closure, drooping of the corner of the mouth, impaired closure of the mouth, dry eye, hyperacusis, impaired taste, or pain around the ear [1]. Initially, PFP is treated with different strategies, including the use of steroids, antivirals and physiotherapy [2]. As nerve regeneration occurs and the patient achieves a moderate degree of muscle contraction, neuromuscular reeducation exercises are started aimed at facilitating motor return. These exercises aim to create new pathways through neural plasticity to improve facial function, so they require frequent practice [3]. Patients can learn appropriate movement patterns through visual biofeedback.

The COVID-19 pandemic has affected the rehabilitation of many PFP patients, as they do not assist to the clinic afraid of being infected; so alternative technologies for remote rehabilitation are required. A remote biofeedback system was developed for the management of patients with PFP, named Facial Therapy (FT). The system allows real-time interaction between the health professional and the patient through a virtual platform. It automatically locates the mouth corners, showing the displacement through two color indicators that provide displacement augmentation so the movements are more obvious to the patient and therapist. During therapy, the patient is asked to smile, registering the activity mainly of the zygomaticus and risorius muscles bilaterally. FT makes it possible to visually recognize muscle displacement, facilitating both relaxation and balanced re-education of the desired muscles, reinforcing the sensitive recognition of proprioception through vision. An initial pilot study has shown promising results. Currently a longitudinal clinical trial is underway and the results will be presented at the conference.

References:

- Roob G, Fazekas F, Hartung HP. Peripheral facial palsy: etiology, diagnosis and treatment. Eur Neurol. 1999 Jan;41(1):3-9.
- Baugh RF, Basura GJ, Ishii LE, et al. Clinical practice guideline Bell's palsy. Otolaryngol Head Neck Surg 2013;149:1-27.
- Facial rehabilitation: a neuromuscular reeducation, patient-centered approach. Facial Plast Surg 2008;24(2):250-9.

This work was supported by:

Aldawa Technologies, Instituto Nacional de Neurología y Neurocirugía

Sucar, L. Enrique ^{1,2}; Valdivia, Roberto ²; Serrano-Pérez, Jonathan ¹; Torres, José Alfredo ³; Méndez, Karla ⁴; Perera, Nelly ⁵; Hernández-Franco, Jorge ⁵

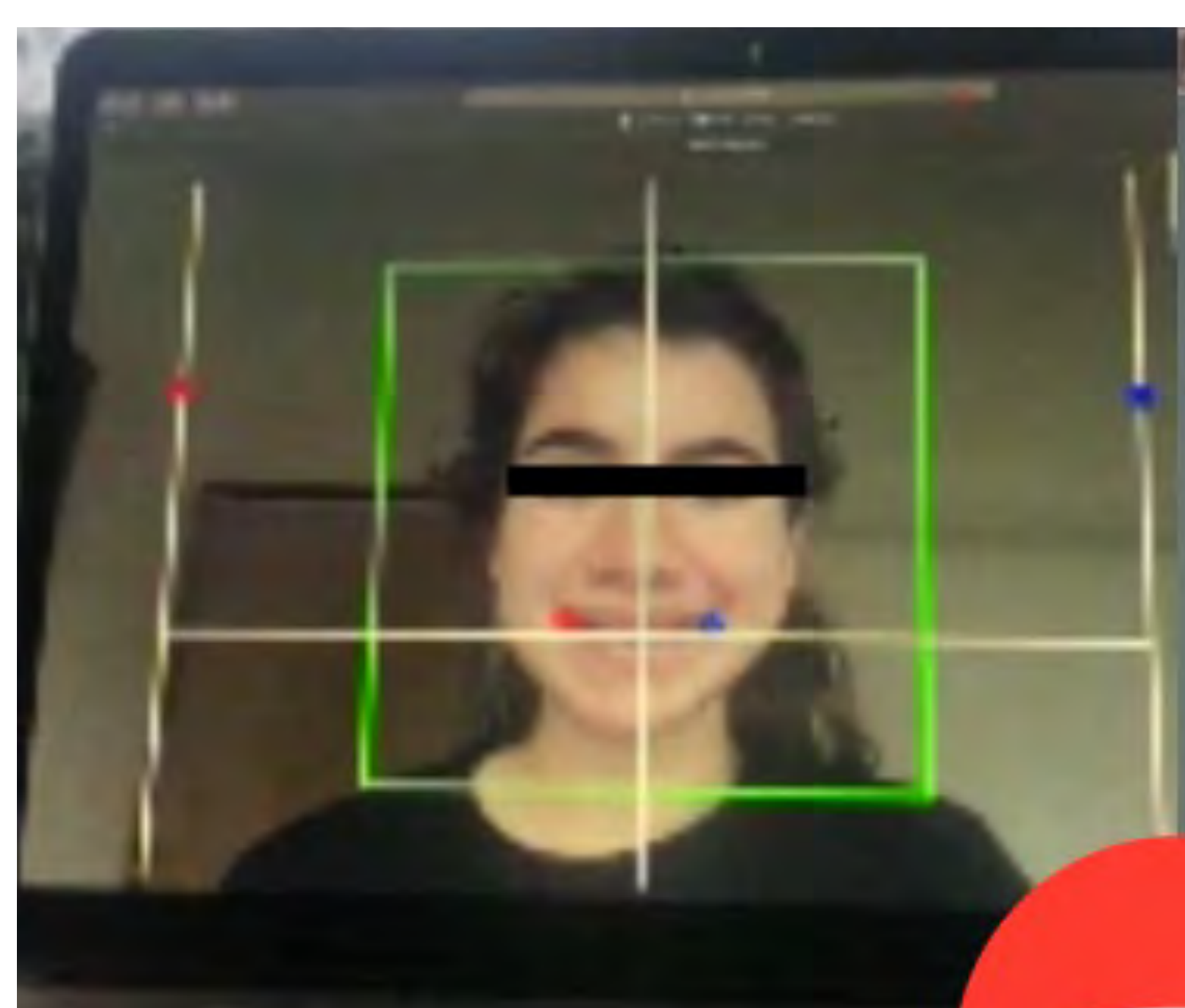
1: Instituto Nacional de Astrofísica, Óptica y Electrónica, Puebla, Mexico; 2: Aldawa Technologies, Puebla, Mexico; 3: Tecnológico de Monterrey, Tampico, Mexico; 4: Universidad de las Américas, Puebla, Mexico; 5: Instituto Nacional de Neurología y Neurocirugía, Ciudad de México, Mexico

Problem:

- Peripheral facial palsy (PFP) is a cranial mononeuropathy that affects 30/100,000 persons, associated with weakness of the facial nerve.
- Initially, PFP is treated with different strategies, including the use of steroids, antivirals and physiotherapy.
- As nerve regeneration occurs, neuromuscular re-education exercises are started to promote neural plasticity to improve facial function.
- Patients can learn appropriate movement patterns through visual biofeedback.
- The COVID-19 pandemic has affected the rehabilitation of many patients, as they do not assist to the clinic afraid of being infected; so alternative technologies for remote rehabilitation are required.

Methodology:

- Facial Therapy (FT) is remote biofeedback system for the management of patients with PFP.
- It allows real-time interaction between the health professional and the patient through a virtual platform.
- It automatically locates the mouth corners, showing the displacement through two colour indicators that provide displacement augmentation.
- During therapy, the patient is asked to smile, registering the activity mainly of the zygomaticus and risorius muscles bilaterally, as one of the main problems for the patient is to recover the movements of the mouth.
- FT makes it possible to visually recognize muscle displacement, facilitating both relaxation and balanced re-education of the desired muscles, reinforcing the sensitive recognition of proprioception through vision.



The image shows a patient interacting with Facial Therapy.

The red and blue circles show the detection of the mouth corners, whose movement is amplified in the lateral bars (biofeedback)

Results:

- An initial pilot study has shown promising results.
- Currently a longitudinal clinical trial at the National Institute for Neurology and Neurosurgery (INNN) is underway.
- Results from the first two patients denote a significant improvement according to the clinical scales:

Age	Time of evol.	No. Ses.	Initial HB	Final HB	Initial SB	Final SB	Improvement
26	12	11	3	2	21	38	17%
40	36	10	3	2	13	80	65%

- HB: House-Brackman scale (1 – 6, 1=normal facial function)
- SB: Sunnybrook facial grading system (0 – 100, 100=normal))

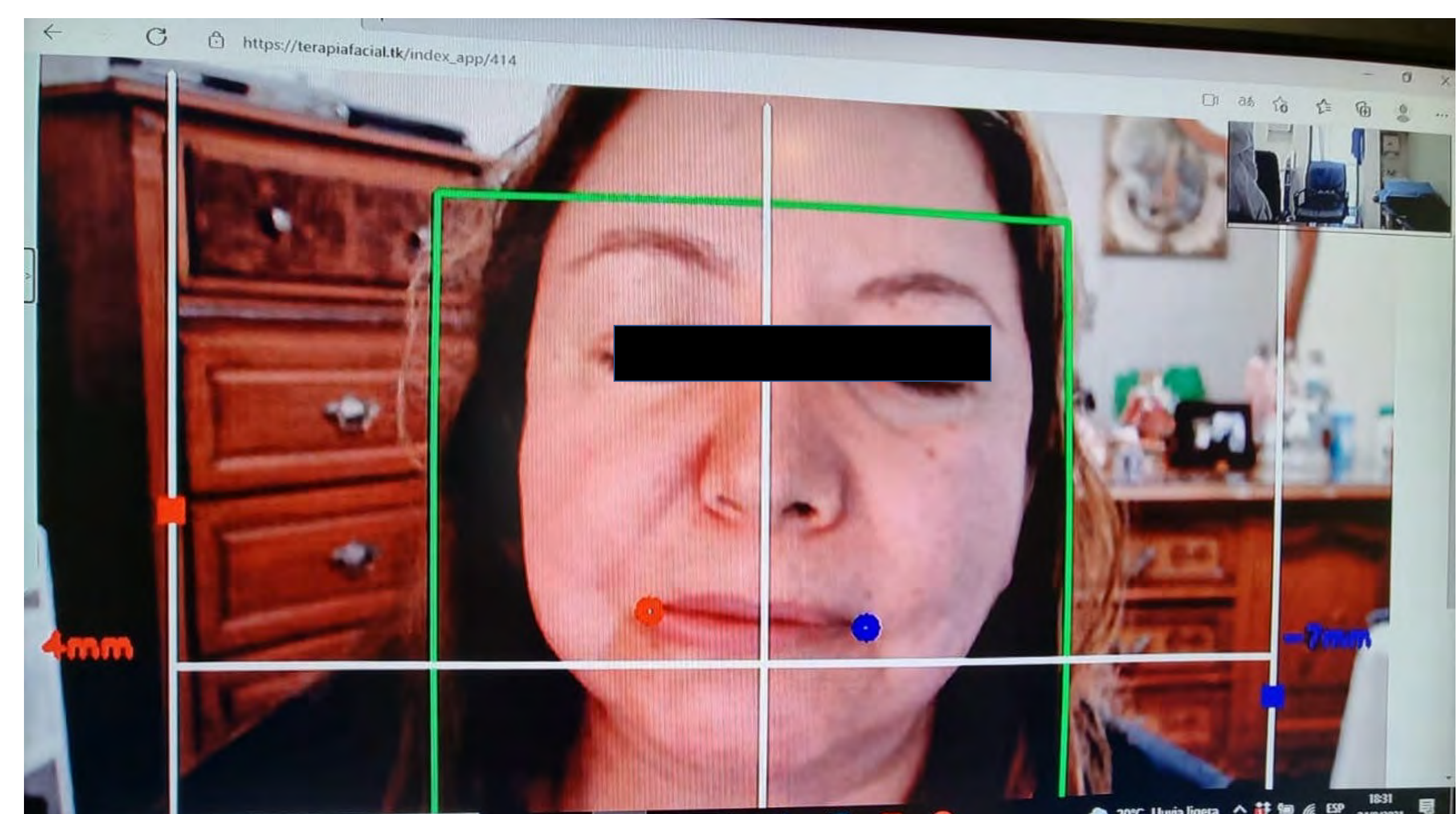


Image of a patient interacting with FT in a rehabilitation session during the clinical trials. An estimate of the displacement of the mouth corners is depicted in mm

Conclusions and Future Work:

- The confinement and reduction in external mobility due to COVID has caused telemedicine to acquire greater relevance these days with a clear tendency to continue increasing its use.
- Initial tests of FT show promising results, with a significant improvement according to clinical scales; and positive comments from both, doctors and patients.
- As future work we plan to conclude the clinical trails and promote the use of this technology for remote facial palsy rehabilitation.

References:

- [1] Roob G, Fazekas F, Hartung HP. Peripheral facial palsy: etiology, diagnosis and treatment. Eur Neurol. 1999 Jan;41(1):3-9.
- [2] Baugh RF, Basura GJ, Ishii LE, et al. Clinical practice guideline Bell's palsy. Otolaryngol Head Neck Surg 2013;149:1-27.
- [3] VanSwearingen J. Facial rehabilitation: a neuromuscular reeducation, patient-centered approach. Facial Plast Surg 2008;24(2):250–9.

Type of submission: Scientific Poster

Feasibility of Adaptive Gait Support in a Robot-Aided Gait Trainer (Lokomat) in Neurological Disorders

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Presenting author: Munari, Daniele

Walking impairment in neurological disorders can be addressed with intensive, task-specific locomotor training. The training intensity can be increased with robotic devices. Most robotic gait trainers provide constant assistance without considering each patient's functional ability. In the Sensation software, the Lokomat implements an Adaptive Gait Support (AGS) algorithm, that automatically adapts the hip and knee robotic support (i.e. the Guidance Force) based on the patient's ability to follow a reference gait pattern. The support targets specifically the different phases of the gait cycle, increasing only when needed. AGS could be used as training tool (to optimally challenge the patient) or to assess walking ability (the level of robotic support determined by AGS should be proportional to the patient's impairment [1]). The aim of this study was to examine the feasibility of the AGS in an 8-week training period in 10 patients with different neurological diagnoses and to assess the relationship between the robotic support determined by AGS and conventional walking tests. We also examined the difference between robotic support determined by AGS and robotic support applied in conventional Lokomat training.

The results show that AGS is feasible in patients with diverse neurological disorders and severity. The robotic support set automatically with AGS was on average significantly lower than the support provided during conventional Lokomat training, possibly indicating higher patient's challenge. Further studies should explore if training with lower, and adaptive, robotic support results in a more effective training. The robotic support set by AGS correlated with the patient's gait impairment, suggesting good potential of AGS for assessing walking ability.

References:

- S. Maggioni, „Robot-Aided Gait Assessment and Rehabilitation: an Assist-as- Needed Approach,“ Ph.D. dissertation ETH Zurich, p. 93–118, 2019.

This work was supported by:

Type of submission: Clinical Poster

The Use of C-Mill VR+ for Rehabilitation of Balance and Gait Adaptability Training in a Chronic Traumatic Injury Patient.

Küçükçakır, Nurten ¹; Çalışır, Nermin ¹; Tefenli, Beyza ¹; Akıncı, Hayrullah ¹; Aktaş, HasanAli ¹; Aktaş, Rafet ¹; Yılmaz, Anıl ¹.

1: Romatem Physical Therapy And Rehabilitation Hospital, Bursa , Turkey

Presenting author: KÜÇÜKÇAKIR, NURTEN

We would like to share our clinical experience with a chronic patient that suffered a traumatic brain injury. The patient applied to our facility for the purpose of rehabilitation more than 8 years after the incident. An intensive training combining conventional therapy and also robotic therapy, including the C-Mill VR+, was provided in our facility for months.

We took the tests: Tinetti balance and walking test, Berg balance scale, Tandem stance and gait test, and functional ambulation classification at 1, 8, and 17 weeks and the data on the C-Mill.

We worked with adjustable speeds on the treadmill by connecting with a parachute system and a corset up on the C-Mill device. After our patient understood that he would not fall with safety precautions, we were able to practice standing, balance and walking for 45 minutes under the supervision of a single physiotherapist. Seeing parameters such as step width, walking speed and distance, weight transfer in the computer environment during and after the C_Mill sessions, comparing the weekly developments and seeing the reports increased the motivation of the patient. Thanks to the visual and auditory stimuli on the opposite screen and in the walking area, we were able to practice not being distracted.

The patient's experience with improved outcomes, even after 8 years after his incident, and the improvements in efficiency, gestion of resources and time motivated us to share how the C-Mill can be incorporated into a program with this patient population.

References:

This work was supported by:



The use of C-Mill VR+ for balance and gait adaptability training with a patient with chronic Brain Traumatic Injury

Küçükçakır, Nurten; Çalışır, Nermin; Tefenli, Beyzanur ; Akıncı, Hayrullah; Aktaş, HasanAli; Akar, Rafet; Yılmaz, Anıl

Romatem Physical Therapy and Rehabilitation Hospital, Bursa.Turkey

ROMATEM



1 PATIENT'S HISTORY/ANAMNESIS

Mr F J, 36 years old, male, 2011 had an accident . He suffered multiple trauma including **traumatic brain injury**. He was in the intensive care unit in a coma for 4 months, and after 7 months he was able to sit with support but **could not stand up**. The patient applied to the Romatem Bursa Physical Therapy and Rehabilitation Hospital in February 2020 for the purpose of rehabilitation. The first assessment was:

Cooperative and oriented patient

Dysarthric speech

Muscle strength is 5/5

Bilateral dysmetria, dysdiadochokinesis, prominent on the left.

Tandem stance and tandem walk test could not be performed

Not possible to stand on one leg

Tendency to ataxia and backward fall in all directions

Risk of falling without support is very high

Sitting and standing transfers not alone

Both eyelids cannot be closed secondary to the operation, eyeball movements restricted in all directions: fixed and midline and vision 3/10

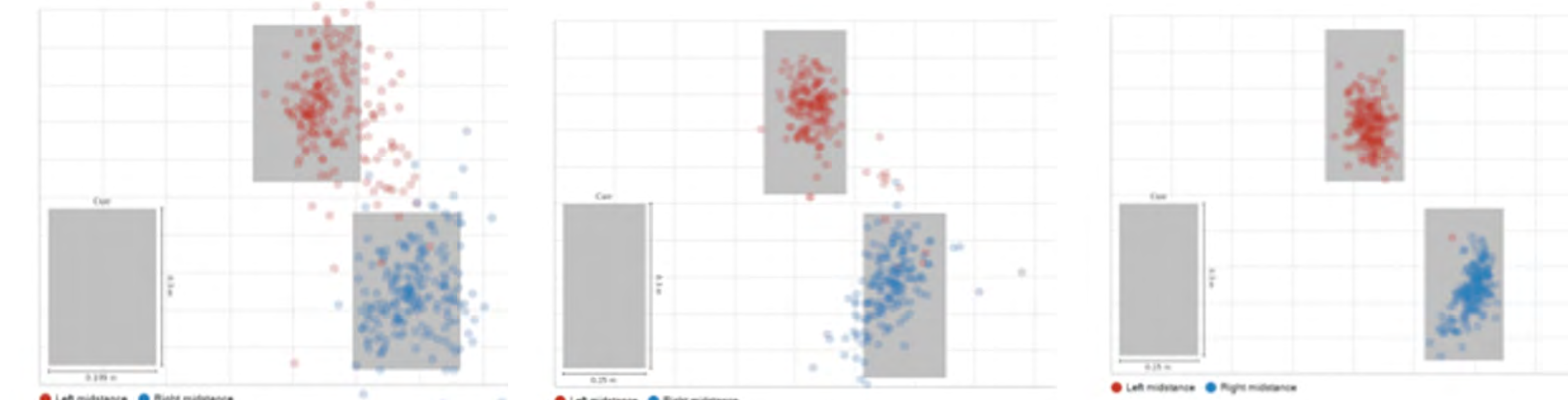
The patient started an intensive rehabilitation program in Romatem Bursa Hospital with 4 to 7 days a week therapy, 2 to 3 sessions a day.

The main problems affecting the daily life of the patient were lack of balance, ataxic gait, risk of fall, vision loss - diplopia.

In October 2020 the patient was included in the **balance and walking rehabilitation program with the C-Mill in addition to other rehabilitation programs**. The C-Mill program included sessions of 40 min repeated two to three times a week, on a total of 17 weeks.

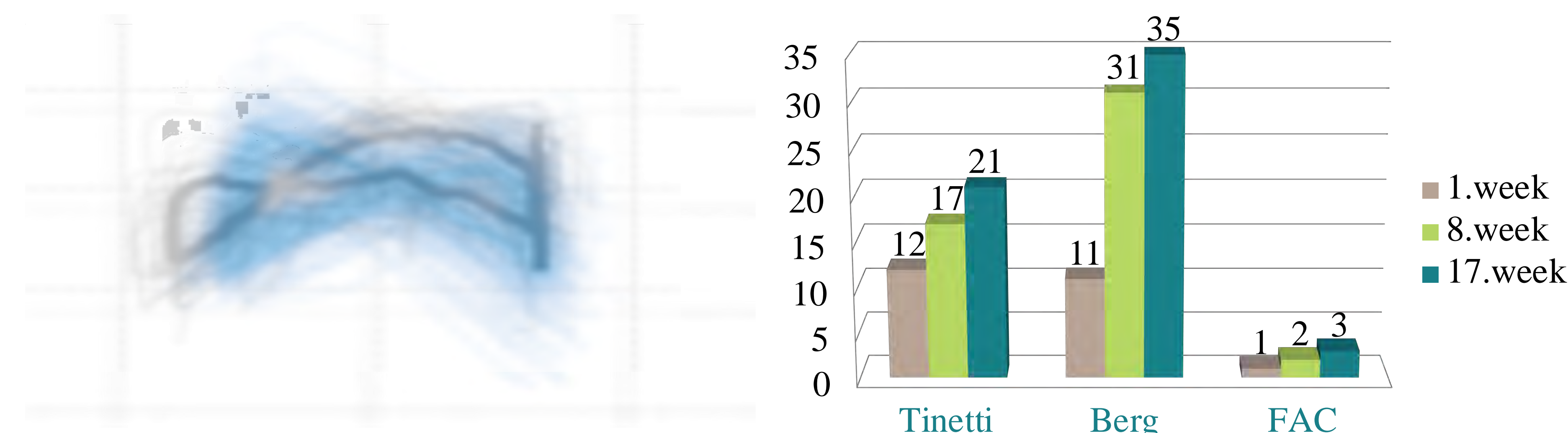
2 RESULTS

The first day of the C-Mill therapy the balance assessments (postural stability and limits of stability) and the gait assessment were performed on the device. Tinetti, Berg balance scale, Tandem stance, gait test, and ambulation classification were also performed. The same tests were repeated after 8 weeks and after 17 weeks later. The “**STEPPING STONES**” was one of the chosen **protocols** on the **C-Mill** for the patient **training**.



- First session. The values of the **patient own gait pattern** were taken in consideration and not many changes were done to the stone position. The patient midstance was not always on the stone, specially on the left side.
- Following sessions: Some **modifications** were done using the protocol **settings** in order to modulate the gait pattern of the patient, these modifications included:

- Changes on the **step length**: was **progressively increased** during the sessions. his midstance on the left and right side was each time more inside the stone. It was also a decrease of the width of the stones.
- Changes on the **treadmill speed**: during the first sessions, a treadmill speed of **0.6-0.7 km/h** was selected and the patient could walk for **4 minutes** needing to stop to rest. On the following weeks, the patient's **endurance started to increase significantly** so the treadmill speed was increased to **1-1.2 km/h** and the walking time was gradually increased to 6 min-8 min and finally **10 min**.
- Support**: In the first days the patient needed to support himself with **both hands** on the handrails. After 4 weeks, he could walk with **one hand** support in “stepping stones” protocol for 10 minutes without disturbing his balance.



December 2020

March 2021

3 DISCUSSION

- Only one therapist needed instead of two.
- In CT only available 10 minutes for walking, with the C-Mill 40 minutes (stand, step, walking).
- C-Mill provided **detailed reports** automatically increased the motivation, as well for the patient than for the therapists.
- C-Mill reduce the external disturbances, **focusing** the patient into the **exercises** thanks to the **VR** and **AR**.
- The patient had visual problems, so it took some sessions to get use it. But visual perception increased and adaptation improved.
- Walking on the treadmill was more difficult and a constantly need to check the stopping-holding-balance. After realizing that he would not fall, he continued his exercises much more comfortably.



He was **tired** of being in hospital-rehabilitation environments for **9 years** and he was demoralized by thinking that there was **no improvement** and would not happen. For this reason, his participation in rehabilitation was very low in some periods.

Seeing the data at the end of the session with the C-Mill motivated him a lot: it was very **effective** to see the **progress** of his steps in the stepping stones module, especially. The patient and his relatives **did not give up**.

We, as the **rehabilitation team**, were constantly thinking about what we could do and when we were desperate, we started working with the **C-Mill**.

4 CONCLUSIONS

The contribution of all other treatments was great, but when we were going to despair at the point where our options were exhausted, the **C mill stepped in**. And the result is our patient who came to our hospital with a **wheelchair**; he was discharged from our hospital **on foot** in July 2021.

Type of submission: Clinical Poster

Masterclass in Neurotechnology (MiNT) – An Innovative Online Educational Platform Embedding the Use of Neurotechnology in Clinical Practice

Bean, Alison ¹; Bryan, Eleanor ¹; Sankovic, Leo ¹

1: Hobbs Rehabilitation, Winchester, UK

Presenting author: Bean, Alison Sarah

Masterclass in Neurotechnology (MiNT) is a structured clinical education programme designed to increase the use of neurotechnology within clinical practice. It combines an innovative online training platform with conferences, practical courses and professional collaboration. Designed by Hobbs Rehabilitation, MiNT aims to address and overcome the current barriers to therapists using technology within clinical settings.

Hobbs identified a disconnect between neurotechnology companies and clinicians. There are also known barriers to implementing neurotechnology in practice, including insufficient evidence and training. However, Hobbs has always valued neurotechnology, recognising its potential to increase therapy dosage and enhance practice. Hobbs collaborates with many technology companies and in 2018 ran its inaugural MiNT conference.

The MiNT concept has evolved into a programme that Hobbs foresees being adopted as the leader in neurotechnology training. MiNT will be hosted via an online platform, on which users are empowered to work through progressive training levels, from introductory modules on neurotechnology rationale, to becoming competent users and device specialists. In addition to online learning, advanced levels will include practical courses and monitored use of devices in clinical practice. The MiNT platform will include a device log for clinicians to record therapeutic usage and provide feedback to product developers. This evidence can also be extracted for academic research. The ability of MiNT to connect clinicians, engineers and academics will build an expert network to help further progress the neurotechnology field.

The MiNT website is currently under development; Hobbs aim to have the platform live by summer 2022. Stakeholder discussions have unanimously supported and acknowledged the necessity of MiNT. Realising this ambition is not only exciting for Hobbs, but could positively transform neurotechnology education and clinical implementation.

References:




This work was supported by:

An Innovative Online Educational Platform Embedding the Use of Neurotechnology in Clinical Practice

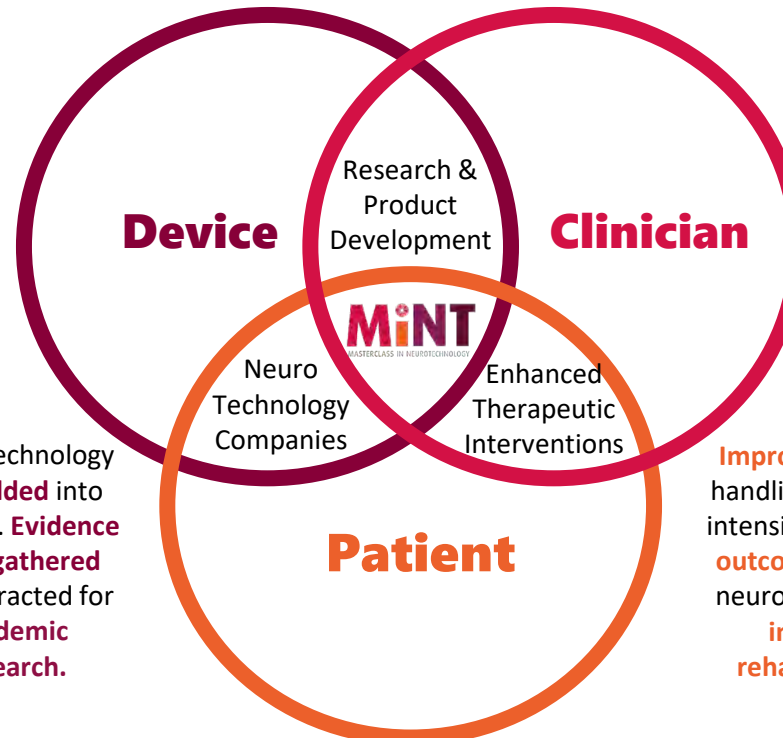
Authors: Bean, Alison; Bryan, Eleanor; Sankovic, Leo.
Affiliations: Hobbs Rehabilitation, Winchester, UK.

Designed by Hobbs Rehabilitation, Masterclass in Neurotechnology (MiNT) provides a universal solution to the current barriers limiting neurotechnology usage within clinical settings. MiNT is a structured clinical educational programme, combining online learning with practical courses, facilitating neurotechnology uptake and embedding its usage within clinical practice. MiNT also provides companies and academics with clinical expertise and data for product development and research, with user driven innovation accessed via Clinical Consultancy Packages.

MiNT Educational Platform

-  **Online Modules:** evidence-based introductory and device-specific e-learning, progressing from Levels 1-5
-  **Practical Modules:** device-specific, in-person, collaborative working and clinical reasoning
-  **Clinical Practice:** log-book use to record clinical data, with opportunity to become a Device Specialist and Trainer




CPD Opportunities: Improved clinical knowledge and skills, **networking** with experts in the field and **progressing neurotechnology development**.



Neurotechnology **embedded** into services. **Evidence to be gathered** and extracted for **academic research**.

Improved patient handling, dosage & intensity. **Enhanced outcomes**; driving neuroplasticity via **intensive rehabilitation**.

MiNT Company Membership

-  Access to a **wider target audience**, via advertising and education on companies' own devices
-  Access to **clinical expertise** and **data** for product development and research, with **user driven innovation** via **Clinical Consultancy Packages**
-  Development of an **open innovation platform** for clinically necessary and relevant product ideas



Type of submission: Clinical Poster

How Robotics Can Be Implemented for Bedside Treatment at Early Stage of Rehabilitation Process

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2.Rehstab Rehabilitation Clinic, 34-600 Limanowa

3.Clinical Department, Egzotech sp. z o.o., 44-100 Gliwice, Poland

Presenting author: Kozak, Dominika

Severe weakness in combination with tubes, lines and machinery are practical barriers for the implementation of movement rehabilitation with critically ill patients. Transferring the acute patient from the patient room to the rehabilitation table is challenging at early stage of rehabilitation[1]. In the ICU, out-of-bed rehabilitation is often delayed and in-bed exercises are generally low-intensity. Since the majority of rehabilitation is carried out in bed, it is essential to carry out the exercises that have the highest intensity[2].

We present an example of implementing robotic rehabilitation technology (Luna EMG) into the early stage of functional recovery of the patient after stroke.

Therapy with the use of a rehabilitation robot was introduced at an early stage of rehabilitation, while the patient was still immobilized in bed, unable to perform active movement. Mainly passive exercises were used, including monitoring of muscle activity by surface EMG. These exercises were aimed at early mobilization and prevention of serious complications due to immobilization. As the patient's functional status improved, he began to gradually switch to assisted exercises. The most unique feature of this device is "EMG-triggered robotic movement", which enables to work actively with patients, even if no movement is visible, but muscle activity is maintained [3].

With the use of different extensions: for shoulder, lower limb and trunk, it was possible to provide the therapy in different positions- from supine lying to sitting for the main body joints. In the pandemic period using robotic devices becomes a tool for physiotherapists to work with more patients at the same time and not allow the staff shortage to influence the neurological patients' condition. In addition the solution can help prevent the immobilisation related problems or help to recover patients after COVID-19 infection if any function has been lost due to neurological complications.

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How robotics can be implemented for bedside treatment at early stage of rehabilitation process

Patrycja Lewandowska-Sroka^{1,2}, Rafał Stabrawa^{1,2}, Dominika Kozak³

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³ EGZOTech, Gliwice, Poland

Introduction

Severe weakness in combination with tubes, lines and machinery are practical barriers for the implementation of movement rehabilitation with critically ill patients. Transferring the acute patient from the patient room to the rehabilitation table is challenging at early stage of rehabilitation[1]. In the ICU, out-of-bed rehabilitation is often delayed and in-bed exercises are generally low-intensity. Since the majority of rehabilitation is carried out in bed, it is essential to carry out the exercises that have the highest intensity[2]. Immobility from prolonged bed rest is associated with many complications, including muscle atrophy, pressure ulcers, atelectasis, and bone demineralization [3].

Luna EMG

Luna EMG is a robotic device used in rehabilitation of neurological and orthopaedic patients, as a training and assessment tool. The most unique feature of this device is "EMG-triggered robotic movement", which enables to work actively with patients, even if no movement is visible, but muscle activity is maintained [4].

Device provides the passive, assistive (EMG driven robotic movement) and resistive types of exercises. EMG-driven robotic technology enables or facilitates patients' movement during the training of upper and lower limbs. In order for a robot to assist with the movement, the patient muscle activity needs to reach the set threshold. This approach is mostly effective with patients suffering from clinical weakness. Different extensions are used to work with shoulder, elbow, wrist, hip, knee and ankle.

Luna EMG was designed to provide a "hands-off" approach, to give more independence to the patient, even when the patient's mobility and muscle activity is very limited. In the face of COVID-19 pandemic, this approach seems to be very beneficial, since it limits the direct contact between the patient and the therapist, while maintaining proper movement assistance and facilitation.

Therapy Example

We present an example of implementing robotic rehabilitation technology (Luna EMG) into the early stage of functional recovery of the patient after stroke. Therapy with the use of a rehabilitation robot was introduced at an early stage of rehabilitation, while the patient was still immobilized in bed, unable to perform active movement. Mainly passive exercises were used, including monitoring of muscle activity by surface EMG. These exercises were aimed at early mobilization and prevention of serious complications due to immobilization. As the patient's functional status improved, he began to gradually switch to assisted exercises.

It is recommended to exercise 15-30 minutes for one joint and starting therapy with CPM or Progressive CPM (5-10 minutes). To start exercises in supine position and then move into sitting position (depending on patients condition).



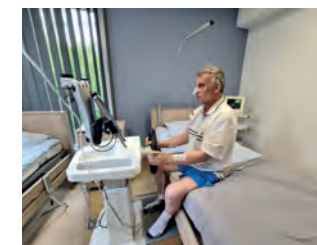
To start exercises in supine position and then move into sitting position (depending on patients condition)



Weak patient (even unconscious) no muscle contraction- use CPM (passive movement) to prevent joint contractures.



Active assistive exercises with Luna EMG



EMG-biofeedback to improve the trunk activity in supine and sitting position (balance training)



Conclusion

Early post-stroke rehabilitation is feasible, safe, and beneficial in critically ill patients. Such early interventions result in better functional outcomes at hospital discharge[5]. In the pandemic period using robotic devices becomes a tool for physiotherapists to work with more patients at the same time and not allow the staff shortage to influence the neurological patients' condition. In addition the solution can help prevent the immobilisation related problems or help to recover patients after COVID-19 infection if any function has been lost due to neurological complications.

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Type of submission: Clinical Poster

The Use of Robotic/Computer Assistive Technologies (R/CAT) During Upper Limb Rehabilitation Therapy Sessions

Abraham, Vicki ¹

1: International Specialised Skills Institute

Presenting author: Abraham, Vicki

People who have experienced a stroke have a big challenge ahead of them to regain their independence in daily activities. It is an important role for occupational therapists to provide these clients with every opportunity to regain maximum function of their affected upper limb, to reach the level of independence and quality of life they desire. R/CAT are being used in clinics all around the world as a form of intensive upper limb therapy. This intensive therapy targets increasing functional use of clients' affected upper limbs. Executive research literature demonstrates that in order for neurological rehabilitation to be effective, especially of the upper limb, treatment needs to be intensive and include extensive repetition of desired movements. Without client motivation, therapy may not be successful. Intensive traditional therapy is difficult for both the client and therapist as it can be physically exhausting for them both, often non-engaging (unless the therapist can keep the client motivated throughout each session) and perceived as boring. With tight hospital financial budgets, intensive treatment is not made available. R/CAT has addressed all of these issues as the devices cannot become tired during a therapy session, the software keeps the clients engaged and the feedback enables the clients to remain motivated. Therapists using R/CAT can achieve better outcomes compared to conventional therapy modalities. Longer term R/CAT may also be more cost effective than traditional intensive therapy. Using R/CAT techniques are beneficial to regaining functional use of an affected upper limb post stroke. Technology is a growing industry, and it has become a part of everyone's daily life. All generations are using various types of technology throughout their daily activities and so it should also be embraced as part of occupational therapy. R/CAT have been successfully incorporated into therapy within a Melbourne clinic and the results have been remarkable.

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This work was supported by:

Abraham OT Services 1, Tyromotion 2

Type of submission: Clinical Poster

Integrating a Robotic Assisted Gait Training Device, LEXO(R), Into Clinical Practice: Gold Standard Treatment Approach

Biddiscombe, Anna; Mance, Camille; McConaghy, Melissa.

Advance Rehab Centre, Sydney, Australia; Macquarie University, Sydney, Australia.

Presenting author: Biddiscombe, Anna

In October 2020, Advance Rehab Centre installed a robotic assisted gait training device - LEXO®. Clinical experience and research conducted have been used to develop the Gold Standard Treatment Approach to effectively integrate LEXO® therapy in a neurorehabilitation setting.

A quality assurance project was completed to determine how LEXO® therapy was delivered to the first 50 clients with a diverse range of chronic neurological disorders. Clients achieved an average of 1064 steps during 17-minute session. One third of clients completed more than 10 sessions across a 3-month period. Clients were making small functional gains, average increase in gait speed of 0.1m/s, but not yet reaching minimal clinically relevant thresholds. Hence, a baseline was set for current therapy delivery and improvements in intensity of therapy and functional gains were indicated. An acceptability and feasibility study was conducted in conjunction with Macquarie University and used to inform our treatment approach.¹ This gave a deeper understanding around the client experience and motivation for using LEXO®. Clients enjoyed the experience of walking on LEXO®, felt safe and believed LEXO® improved their walking overground post session. The study also revealed unique experiences of delivering LEXO® therapy from a physiotherapist's perspective including a perceived reduction in manual effort for therapists. We consulted the evidence base to establish the dosage most likely to be effective on LEXO® based on prior research of stepping intensity and frequency in post-stroke clients.^{2,3}

This informed the Gold Standard Treatment Approach for LEXO® Therapy. For gait retraining we recommend intensive block-based therapy, with a minimum of 3 x 90-minute sessions weekly. These sessions include 60 minutes dedicated to LEXO® therapy and 30 minutes overground walking after LEXO®. The aim is to achieve 3000+ steps and at least 12 minutes in a moderate heart rate training zone.

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This work was supported by:

In October 2020, Advance Rehab Centre installed a robotic assisted gait training device - LEXO®. Clinical experience and research conducted have been used to develop the Gold Standard Treatment Approach to effectively integrate LEXO® therapy in a neurorehabilitation setting.

FIRST 50 CLIENTS ON LEXO®

n=40	Average [range]
No. sessions in 3 months	7 [1-19]
Therapy time (minutes)	17 [13-25]
Steps (steps)	1064 [589-1541]
Distance (metres)	575 [311-862]

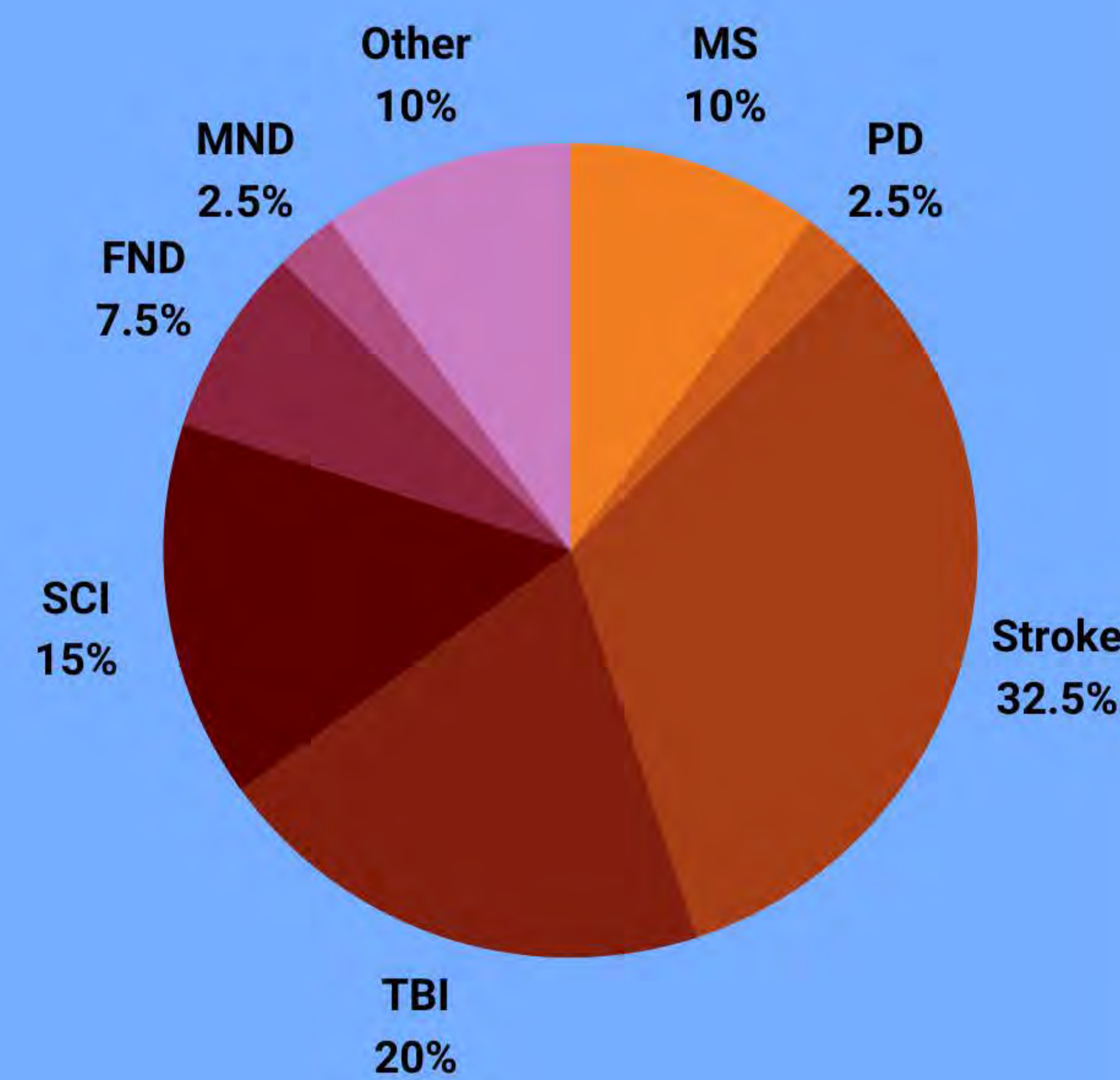
Achieving more steps in less time than typical physiotherapy sessions.[1,2]

>3000 steps is required to drive improvements in walking pace, gait symmetry and daily stepping.[2,3]

Average cadence = 63 steps per minute. At this pace clients need 48 minutes of active therapy time to achieve above 3000 steps. 60-minute booking to accomodate transfers.



Previous research suggests a relationship between cardiovascular demands and neuromuscular activity with treadmill walking and robotic assisted gait training.[2]



FUNCTIONAL GAINS OVER 3 MONTHS

Average gait speed increased 0.1m/s
 minimal clinically important difference = 0.16m/s[4]

Average gait endurance increased 19m over 6MWT
 minimal clinically important difference = 65 metres[5]

Clients who did >10 sessions showed higher gains in walking speed and endurance

GOLD STANDARD TREATMENT APPROACH FOR LEXO® GAIT RETRAINING



Minimum 3 x weekly sessions of 60 minutes on LEXO + 30 minutes overground walking

Aim for 3000+ steps per session and 12 minutes working in a moderate heart rate zone



Suitable for clients with mobility goals and adequate cardiovascular fitness levels



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ACCEPTABILITY AND FEASIBILITY

Macquarie University Study Insights [6].

"I think it's less effortful because the clients is supported by the harness. LEXO® is facilitating the movement so it takes away a lot of the manual assistance" PT#6

"I like it. I find it to be really quite a helpful piece of equipment to use with clients." PT#3

"It's not particularly difficult to do either transfer, it's just more time consuming if you have a client who is unable to stand." PT#6

"It is actually very simple and straightforward to operate." PT#5

Physiotherapists were 80% satisfied and confident

"The LEXO® was also a cardiovascular workout as well as working the gait issues we were looking to correct." Client #3

"I couldn't lift my legs up...to make a step, but as soon as I used the LEXO®...I found that my legs were automatically lifting off the ground." Client #2

"I would love to have some more sessions on LEXO®." Client #4

Clients were 90% satisfied and confident

"I think LEXO® is wonderful and please give us something where you have a drink of water" Client #1

Type of submission: Clinical Poster

Discovering Innovation in Existing Rehabilitation Technologies

Walter, Amber ¹; Dickey, Emily ¹; Vaught, Jessica ¹; Drake, Elisabeth ¹; Holmes, Alina ¹

1: Sheltering Arms Institute

Presenting author: Vaught, Jessi

At Sheltering Arms Institute, an inpatient rehabilitation hospital, we are fortunate to have nearly 20 different rehabilitation technologies available to improve patient outcomes. We have been through processes to evaluate effectiveness and adoption of these technologies, presenting previously on how we sustain use of technology in inpatient and outpatient neurologic rehabilitation clinics. We found value in concerted efforts toward standardized training, refining use and training over time, and measuring outcomes. Now our teams are developing innovative ways to utilize rehabilitation technologies: with activities not considered in vendor-offered clinical training, use of combinations of technologies, or use with non-traditional therapy disciplines. This innovative use meets the primary goal for therapists in technologies – to benefit their patients(1,2). Specific pictorial examples using patient case details will be given to demonstrate how the devices don't do the hard work, it's skilled clinicians applying the technology to make a difference.

One example presented is transforming the use of body weight support beyond gait training. Our physical and occupational therapists collaborated to develop training and a quick guide of activities that occupational therapists could perform within their treatment sessions utilizing body weight support. In this guide, examples are given for how the occupational therapist would be able to maximize their own facilitation to the patient when the patient is supported within the body weight support technology. Our aim for readers of the poster is to begin thinking beyond standard uses of technology and how to leverage technology in innovative ways to support patient outcomes.

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This work was supported by:

Type of submission: Industry Poster

Fourier Intelligence RehabHub™

Kee, Jake¹; Leong, Kenneth¹; Lim, Sarah¹; Teoh, Owen¹;

1:Fourier Intelligence

Presenting author: Lim, Sarah

Fourier Intelligence RehabHub™ is a total solution concept consisting of comprehensive advanced rehabilitation technology including robotics therapy, neuromodulation, sensor technology, virtual reality, and functional electrical stimulation. The principle of RehabHub™ technology is to provide high-efficiency rehabilitation training, cost-effective therapy outcome and emphasises space-saving and ease of use. The 5 main application settings of the RehabHub™ are neurological rehabilitation, sports rehabilitation, vocational training, pain management and healthy ageing.

The group therapy concept leveraged the advantages of having multiple advanced rehabilitation robotics in the RehabHub™ allowing patients to have a cooperative or competitive training environment. Besides, the social interaction in the group therapy not only will retain the patient's interest and motivation in rehabilitation also helps with post-injury depression and avoidance of social withdrawal.

Fourier Intelligence established a strong strategic alliance worldwide with the forthcoming technology providers to provide the most comprehensive solution of the RehabHub™. Each of the strategic alliance partners comes from the five different sectors of the advanced rehabilitation technology to achieve the goal of 'Rehabilitation for All' through the RehabHub™.

The RehabHub™ serves as a platform that allows the technologies from all the strategic alliance partners to be integrated. Besides, the RehabHub™ integration with the hospital information system (HIS) allowing the clinician to easily access, operate and monitor the patients.

Fourier Intelligence aims to accelerate the adoption of advanced rehabilitation technology and make technology mainstream by fully integrating them into the clinical settings, hence creating positive clinical outcomes.

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This work was supported by:

RehabHub™

Fourier Intelligence RehabHub™ is a total solution concept consisting of a comprehensive advanced rehabilitation technology including robotics therapy, neuromodulation, sensor technology, virtual reality, and functional electrical stimulation.

The principle of RehabHub™ technology is to provide high-efficiency rehabilitation training, cost-effective therapy outcome and emphasizes space-saving and ease of use.



A fully digitised training environment reduces the labour-intensive work of physical therapists so that they can focus on diagnoses, therapy planning, and dexterous manual therapy.

Virtual Reality



Robotics Therapy



Functional Electrical Stimulation



Sensor Technology



Neuromodulation



Gamified Training

Gamified training acts as an intermedium, bringing several patients together to interact and complete a common goal.

The integration of video games into rehabilitation robotics allows therapy to be more fun and motivating. The joy of completing the goals in the game will make the patient temporarily forget about their pain and illness.



Strategic Alliance

Fourier Intelligence established strong strategic alliances worldwide with forthcoming technology providers to provide the most comprehensive services of the RehabHub™.

Each of the strategic alliance partners comes from the five different sectors of the advanced rehabilitation technology to achieve the goal of 'Rehabilitation for All' through the RehabHub™.

The RehabHub™ integration with the hospital information system (HIS) allowing the clinician to easily access, operate and monitor the patients.

Group Therapy

The group therapy concept leverages the advantages of having multiple advanced rehabilitation robotics in the RehabHub™ allowing patients to have a cooperative or competitive training environment.

The social interaction in the group therapy not only will retain the patient's interest and motivation in rehabilitation and post-injury depression and avoidance of social withdrawal.



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Type of submission: Industry Poster

Connection Is Key - Tyrotherapy Concept for Lower Extremity Rehabilitation

Jakob, Iris ¹; Barbara, Huber ¹; Alexander, Kollreider ¹

1: Tyromotion GmbH, Graz, Austria

Presenting author: Jakob, Iris

Advanced rehabilitation technology can be an important opportunity for the rehabilitation field to increase intensity, dose, and the motivation to train. This is also reflected in current clinical guidelines that generally recommend robotic rehabilitation to improve lower limb motor function, gait, and strength and in standard protocols it seems to be the future of stroke rehabilitation [1].

The number of devices available is growing but often the development and commercialization of specialized stand-alone systems is in focus. On the other hand, clinicians increasingly look for a set of devices that fit together allowing a global upper and/or lower limb treatment, have customized treatments for various patient's characteristics, work in one to one as well as in group settings, hence also result in high utilization rates in the clinical setting [2].

The TyroTherapy concept from Tyromotion is optimized to match patients, clinical, and organizational needs. The alignment of the three key components, which are the technology, the software, and the adaptability, support smooth clinical implementation. An array of robotic and sensor systems provides therapies for the entire upper and lower limb with the right amount of technology and offer impairment-based and task-specific rehabilitation training. The built-in motors of the robotic devices support patients who need assistance and guidance. To maximize active patient participation during therapy, the use of robots transitions to sensor-based feedback systems. For the lower extremity, the functionalities of the two robot-assisted devices LEXO® and OMEGO® Plus complement with the two sensor-based devices TYMO® and PABLO® to address gait therapy goals. All devices are connected by one cross-system software providing a therapeutic gaming environment and a uniform and easy to use interface. The end-effector approach combines high adaptability to a wide patient spectrum with easy and fast setup enabling high utilization rates.

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- www.tyromotio.com

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CONNECTION IS KEY

TyroTherapy Concept for Lower Extremity Rehabilitation

Jakob Iris¹, Huber Barbara¹, Alexander Kollreider¹

¹Tyromotion GmbH, Graz (Austria)

INRS 2021
International Neurorehabilitation Symposium

tyromotion

BACKGROUND

Advanced rehabilitation technology can be an important opportunity for the rehabilitation field to increase **intensity**, **dose**, and the **motivation** to train. This is also reflected in current clinical guidelines that generally recommend robotic rehabilitation to improve lower limb motor function, gait, and strength, and in standard protocols it seems to be the future of stroke rehabilitation [1].

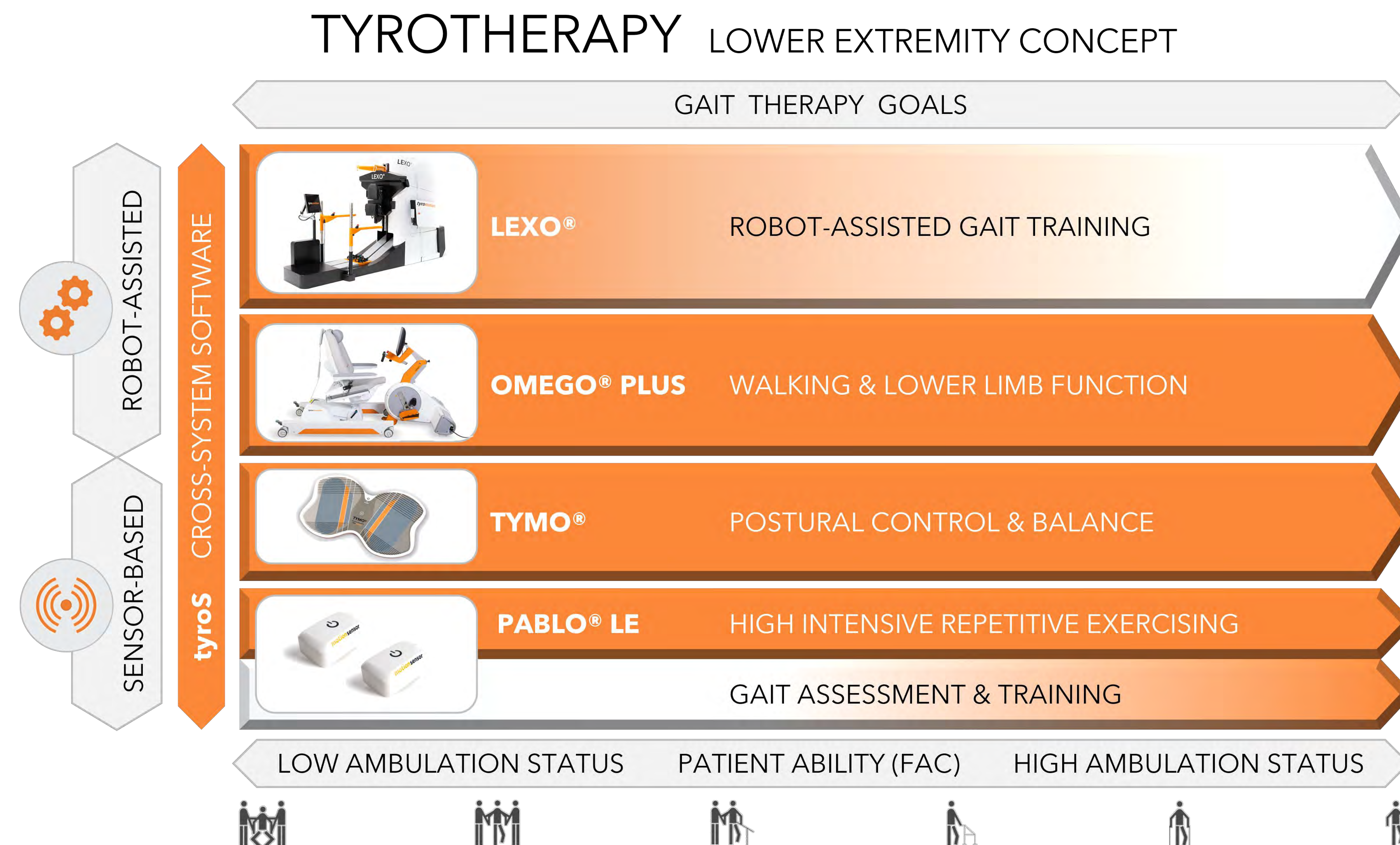
The number of devices available is growing but often the development and commercialization of specialized stand-alone systems is in focus. On the other hand, clinicians increasingly look for a set of devices that fit together allowing a global upper and/or lower limb treatment, have customized treatments for various patient characteristics, work in one-on-one as well as in group settings, hence also result in high utilization rates in the clinical setting [2].

CONCEPT

The **TyroTherapy** concept from Tyromotion is optimized to match patients, clinical, and organizational needs. The alignment of the three key components, which are the technology, the software, and the adaptability, support smooth clinical implementation.

An array of robotic and sensor systems provides therapies for the entire upper and lower limb with the right amount of technology and offer impairment-based and task-specific rehabilitation training. The built-in motors of the robotic devices support patients who need assistance and guidance. To maximize active patient participation during therapy, the use of robot's transitions to sensor-based feedback systems.

For the lower extremity, the functionalities of the two robot-assisted devices **LEXO®** and **OMEGO® Plus** complement with the two sensor-based devices **TYMO®** and **PABLO®** to address gait therapy goals. All devices are connected by one **cross-system software** providing a therapeutic gaming environment and a uniform and easy-to-use interface. The **end-effector approach** combines high adaptability to a wide patient spectrum with easy and fast setup enabling high utilization rates.



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This work was supported by: All the people around the world that challenge the field to Get Better. Every Day!

Type of submission: Industry Poster

From User Feedback to Meaningful Changes: Redesign of the ABLE Exoskeleton

Kreamer-Tonin, Katlin ¹; Lobo Prat, Joan ¹; López Matas, Helena ¹; Garcia Farreny, Alex ¹; Carnicero Carmona, Alfons ¹

1: ABLE Human Motion, Barcelona, Spain

Presenting author: Kreamer Tonin, Katlin

ABLE Human Motion is a medical device start-up based in Barcelona that was born with a clear mission: enabling mobility, for everyone. Therefore, we design, develop and will commercialize exoskeleton technology to empower every person in a wheelchair, by providing better mobility and greater independence.

Our first product is the ABLE Exoskeleton, a lightweight and low-cost wearable robotic exoskeleton that actively assists paraplegic individuals to stand up, walk and sit down. The device consists of a brace that attaches to the legs and torso. Actuators mimic human natural movement, flexing and extending the leg when the intention to take a step is detected using sensors and smart algorithms. The device is accompanied by a cloud-based mobile app to enhance the rehabilitation experience, enabling more personalized therapy with real-time adjustments and quantifiable metrics. The ABLE Exoskeleton provides clinicians with a tool to increase rehabilitation efficiency, and patients with a solution that boosts daily ambulation while empowering them in the community.

The ABLE Exoskeleton is currently going through a prototype redesign based on feedback from usability testing with spinal cord injured (SCI) users. We present how feedback gathered from users with a large range of injury levels has influenced the product. Main feedback was that the device was too physically demanding for higher level SCI individuals, which led to a series of developments to improve trunk support and stability. Major changes include redesign of the hip and ankle joints towards a more natural gait pattern and easier use both for therapists and SCI users. The goal is to make a device that can act as a platform for rehabilitation for users with a broad range of SCI and mobility experiences.

This work shows the value of involving real users during the product development cycle, and how gathering early user feedback can lead to dramatic improvements in technology to really meet their needs.

References:

This work was supported by:

From User Feedback to Meaningful Changes: Redesign of the ABLE Exoskeleton

K. Kreamer-Tonin, H. Lopez, J. Lobo-Prat, A. Garcia, A. Carnicero.

The ABLE Exoskeleton is a lightweight and low-cost wearable robotic exoskeleton to assist people with SCI to walk. It is currently used as a rehabilitation tool.



Lightweight



Intuitive step detection



Tool free adjustment



Physically demanding for users and therapists.



Methods: User testing and feedback



- 36 users
- ABLE, CEN, and Guttman
- C4 to L1, complete & incomplete

Free hip

Poor posture and balance, high effort.

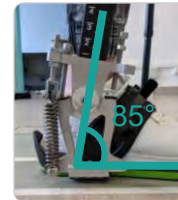


Transparent hip motor

Upright posture is maintained. Focus on walking, instead of using all energy to stay upright.

90° fixed ankle

Challenging to balance, foot not flat on floor.



Articulated spring ankle

User can find balance position. Balance position is usually 85°

Hip belt

Not enough contact area to hold correct posture in high injuries.



Trunk & sacrum support

Back support contacts at sacrum. Feel more secure, especially in higher injuries. Better posture.

Previous design: Specifically tailored to low level SCI, physically demanding.

New design: Platform can be used for many types of injury, less tiring = more time walking.

Type of submission: Industry Poster

An Introduction to Sigma Q (ΣQ®): How Noninvasive Cumulative Charge Activation Technology Alleviates Neuromuscular Pain and Dysfunction

Ciaff, Roberto¹; **Krishen, Lovely**²; **Schmidt, Maria**²; **Schmidt, Steve**²

1: Biosysco Holdings Limited, Cobham, KT11 2LA. United Kingdom

2: Biosysco, Inc., Chicago, IL, United States

Presenting author: Ciaff, Roberto

Over 100M+ Americans suffer from chronic muscle-related pain because of problems with their backs, shoulders, knees, etc., due to injury, aging, diseases, obesity and simple over exertion. This has spawned a prescription drug epidemic that is costing over \$600B annually in healthcare costs [AAPM].

The primary cause of most any muscle related injury or disease is neurological, not topical. When the muscle has either been injured, atrophied or over-worked, the neurological communication between the muscle and the brain becomes compromised and reduced. ΣQ® is a unique, patented neuromuscular technology that delivers a completely different type of signal by utilizing a combination of sound and electricity. This combined signal delivers “charged packets.” These packets generate a signal that replicates the neuro-muscular signals. The sound waves protect the charge and allow the signal to safely enter the body to reach and activate deep rooted nerves & muscles. Once the signal is within the body, the sound carries the variable signal throughout the body and when it finds decompressed nerves, it releases the charge at the synapse nerve causing it to release acetylcholine, thus causing muscle activation & repair. ΣQ® solves the underlying problem for both patients and practitioners because it:

- Actively recovers neuromuscular tissue, it does not just stimulate them
- Effortlessly exercises the muscle, thus eliciting more chemical reactions along the nerve
- Provides biofeedback data from the patient to be used by the practitioner to determine treatment results
- Helps reduce the cost of healthcare by speeding up recovery, while reducing the need for drugs or surgery

As a result, ΣQ® is better able to address the root cause of pain and potentially serve as an alternative therapy to drugs.

In this presentation, ΣQ® inventor & patent holder Dr. Roberto Ciaff will discuss the technology, research and development initiatives, and its real-world applications currently.

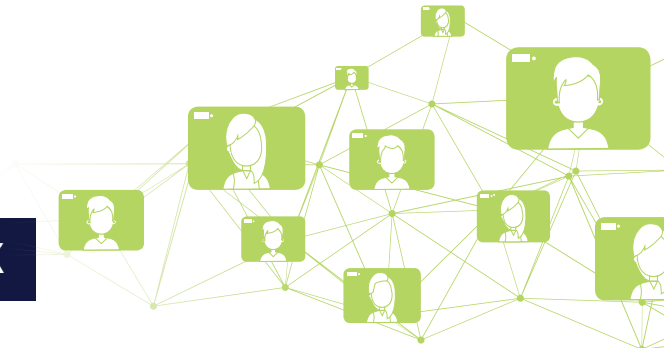
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This work was supported by:



REHAB WEEK 2021

ABSTRACT E-BOOK



REHAB WEEK 2021

23-25 SEPTEMBER 2021
VIRTUAL EVENT



TOPIC: Breaking down barriers to clinical uptake of VR

An Affordable, Wearable Virtual Rehabilitation Setup

Sierotowicz, Marek, 1,2, Castellini, Claudio, 1,2

1: Friedrich Alexander University, Erlangen, Germany; 2: German Aerospace Center, Wessling, Germany

Immersion in a Virtual Reality (VR) environment has recently been proposed as a possible way to treat phantom limb pain by showing amputees an avatar of their missing limb. Most notably, sEMG-based machine learning has successfully been used to implement a VR-simulation showing an amputee a virtual hand, which can be controlled by performing muscle contractions. Such setups often use off-the-shelf hardware, which can still be relatively expensive for an average consumer, and the use of which is typically limited to a restricted space determined by optical equipment used to track the user's position in space.

However, the diffusion of cheap and accurate MEMS IMUs presents us with the possibility of reliably monitoring the user's body pose without the need for any optical equipment. Furthermore, self-contained sEMG sensors, together with computationally efficient intention-predicting algorithms can run hand motion prediction on a smartphone, which can also work as a VR display.

In this study, we introduce an Android-based prototype virtual rehabilitation setup, consisting of a few wearable sensors, allowing a user to experience most of the functionalities offered by other such simulations, while being completely wearable and self-contained thanks to IMU-based body tracking. The overall hardware cost is considerably lower than the average VR setup thanks to the usage of a commercial smartphone.

Such a prototype goes in the direction of making virtual rehabilitation, especially for amputees, broadly available, both within a domestic environment as well as outdoors.

REHAB WEEK 2021

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TOPIC: Breaking down barriers to clinical uptake of VR

Virtual Reality Environment to Increase Caregivers' Participation in Robotics Development

Alves, Silas F. R. 1, Uribe-Quevedo, Alvaro 1; Chen, Delun 2; Morris, Jon 3; Radmard, Sina 3

1 Software Informatics Research Centre, Ontario Tech University, Oshawa, ON, Canada

2 Department of Mechanical Engineering, University of British Columbia, Vancouver, BC, Canada

3 JDQ Systems Inc., Vancouver, BC, Canada

Introduction: Providing care to seniors and adults with Developmental Disabilities presents specific challenges that are being leveraged with emerging technologies such as robotics and virtual reality among others [1]. The current COVID-19 pandemic has intensified the need of technology that can help caregivers to provide care while observing social distance, thus increasing the adoption of robots and VR to help maintain senior's mental and physical health [2]. Herein we present our socially assistive robot "Aether" and a VR environment used to integrate caregivers of our partner long-term care facility (LTCFs) to our development method.

Methods: we created a digital twin of our partner's LTCF to evaluate our robot software using simulation. The digital twin was exported to AltspaceVR where we can connect with caregivers to assess the development without requiring in-person meetings.

Results: The AltspaceVR environment allows caregivers and staff at the LTCF to understand Aether's functionality by observing its responses to their inputs. Preliminary feedback highlights the possibility to use the environment for gathering critique, training staff and promoting the LTCF to the community.

Discussion and Conclusion: The VR environment was positively received by the LTCF due to the immersion provided by navigating the environment and seeing first hand Aether's functionality. We are currently preparing to use this environment to connect with caregivers to evaluate the system and gather their feedback on the robot and on the evaluation process.

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TOPIC: Measuring behavioral change, motivation, engagement in VR

Cognitive stimulation through OroïCognitive, a virtual reality app for older people

Gómez, Adriana, Carreño, Janeth; Berroa, Álvaro; Balenciaga, Ane
Oroi Wellbeing, San Sebastian, Spain; Caser Residencial, Irun, Spain

INTRODUCTION AND AIMS: To analyze the effectiveness of cognitive stimulation carried out through OroïCognitive, a virtual reality app, in older people, as well as its acceptance and attractiveness to them.

METHODS: The research was carried out with 31 participants with a number two or three in the global deterioration scale (GDS).

15 of these participants were part of the control group, and 16 of the experimental group.

The intervention through virtual reality, with exercises more similar to daily activities, allows working on attention, language, memory, orientation, visuospatial skills and executive functions.

It was carried out in 12 sessions, 3 times a week, lasting 25 minutes each one, individually.

Both groups were evaluated using the MINI-MENTAL Cognitive Examination and some subtest of the Weschler Intelligence Scale for adults (WAIS-IV).

RESULTS: Regarding to the effectiveness of the stimulation, the results show significant improvements in vocabulary and information in those with GDS2, in the experimental group.

No statistically significant improvements were found in the rest of the areas. Regarding the assessment of the tool, 69% of the participants rated it as quite useful and interesting. According to the qualitative data collected by the therapists, the users were happier and more animated during and after the intervention.

DISCUSSION AND CONCLUSION: From the observed results, we can deduce that cognitive stimulation through OroïCognitive reduces cognitive deterioration in older people, and improves it in areas related to language. In addition to being an attractive and entertaining intervention for this group.

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TOPIC: Measuring behavioral change, motivation, engagement in VR

Parents & children experiences using a mixed-reality videogame for home-based rehabilitation in children with hemiplegia.

Chan-Viquez, Daniela, Khan, Ajmal; Fehlings, Darcy; Wright, Virginia; Biddiss, Elaine
Rehabilitation Sciences Institute, Faculty of Medicine, University of Toronto, Toronto, Canada.

Institute of Biomedical Engineering , Faculty of Applied Science & Engineering, University of Toronto,
Toronto, Canada.

Holland Bloorview Kids Rehabilitation Hospital, Toronto, Canada.

Introduction: Movement-based videogames are used as a fun home-based rehabilitation alternative for children with hemiplegia. Yet, few research studies have explored parent's and children's experiences to better understand factors influencing motivation and adherence to these interventions. Bootle Blast (BB) is a low-cost, movement-tracking video game designed for upper limb (UL) rehabilitation. BB is mixed-reality: real-life objects are used in gameplay to better target fine motor skills. It is customizable to diverse abilities and therapy goals. This pilot study aims to explore the participant's experiences of using BB at home for 12 weeks in children with hemiplegia.

Methods: Four children-parent dyads played BB at home for 12 continuous weeks, after which participants were individually interviewed (in-person, 20-30 min). This semi-structured interview explored participants' experiences, motivational factors and perceived value of the intervention. Verbatim transcripts were reviewed, assigned codes, and then grouped into potential themes and sub-themes to show patterns in participant responses using a descriptive, inductive thematic approach. Participant characteristics (e.g., age) were considered to understand the context of the individual's experiences and perspectives.

Results: Five themes described the participant's experiences with BB: 1) usefulness for UL therapy, 2) motivational factors (e.g., multiplayer mode, game rewards), 3) benefits of virtual home-based therapy, 3) time constraints, and 4) system improvements.

Conclusions: A videogame system and an intervention protocol that is family & client-centred, allowing for flexibility and adaptability to the individual child's needs, is key for participation in and enjoyment of home-based rehabilitation interventions using videogames.

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23-25 SEPTEMBER 2021
VIRTUAL EVENT



TOPIC: Measuring behavioral change, motivation, engagement in VR

MOTIVATION FOR REHABILITATION: Young people with brain injuries' experiences of virtual reality innovations for therapy

Green, Dido, Boltin, Shana; Gowing, Francesca; Hutchon, Alex; Kilbride, Cherry; Hutchon, Betty
Professor Green and Dr Kilbride, Brunel University London, Department of Health Sciences, London, UK

Professor Green, Department of Rehabilitation, School of Health and Welfare, Jönköping University,
Jönköping, Sweden

Professor Green, Dr Kilbride, Dr B Hutchon, Shana Boltin, Alex Hutchon and Francesa Gowing, Royal Free
London NHS Foundation Trust, Therapies Department, London, UK

Introduction: Intervention programmes for children and young people (CYP) with motor disorders often require extensive repetition of exercises which some CYP find tedious or difficult to adhere to. This study investigated how provision of virtual interfacing access to commercially produced Virtual Reality (VR) games via affordable technologies can provide a motivating environment to improve reaching and hand movements.

Methods: Qualitative analyses of data from a case series study using Raspberry Pis and Oculus Quest for accessibility and full immersion. Three CYP with motor impairments and 6 CYP without movement difficulties participated in a 2-week home-based trial modified due to COVID-19 restrictions. Individual perspectives were gathered from likert and semistructured questions from the Co-Produced User Evaluation and user experience diaries. Thematic analysis identified themes which were mapped against motivational constructs of autonomy, relatedness and self-efficacy/competence.

Results and discussion: Four main themes of persistence, enjoyment, skill acquisition and technology access emerged reflecting key motivational constructs of relatedness and competence with autonomy; the latter negatively influenced by difficulties of access. Exemplary comments included: "It was brilliant"; "I was able to rotate my hands a lot more"; "I have done more exercise on the VR headset than in whole of lockdown"

Conclusions: Preliminary findings reflect potential for affordable, acceptable and accessible VR systems utilizing commercially produced games to be enjoyable and motivating. Findings related to feasibility to impact on upper limb skill are reported in a companion paper. Difficulties were experienced by therapists in setting up the technologies and resolving glitches during the project.

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TOPIC: Virtual agents and Avatar

Training with Agency-Inspired Feedback from a Sensor Glove in Virtual Reality to Improve Grasp Performance

Liu, Mingxiao, Sanford, Sean; Wilder, Samuel; Nataraj, Raviraj

Graduate research assistant, Movement Control Rehabilitation Lab, Biomedical Engineering, Raviraj Nataraj (PI), Stevens Institute of Technology, Hoboken, NJ, USA

Neurotrauma such as spinal cord injury (SCI) traumatic brain injury (TBI) and stroke can have significant impact on people's activities of daily livings (ADLs), especially reaching and grasping [1, 2]. Physical therapy (PT) has been the primary method to help individuals suffered from these neurotrauma to regain or retrain hand functions such as grasping [3]. However, commitment to PT can be challenging, which involves repetitive and intensive rehabilitative training [4]. Also, conventional PT methods have yet to effectively leverage consideration of cognitive factors, whereas the emphasis is on the perception of self-control. Sense of agency or agency has been previously studied to better motivate people to engage in movement learning [5]. The preliminary study leveraged agency and presented a novel approach using a sensor glove to identify achievement of a "secure" grasp and to provide training feedback to improve grasp performance such as pathlength and completion time. Virtual reality (VR) is often involved in PT to provide customized, gamified and enhanced feedback during rehabilitation [6]. In this study, we aim to integrate VR immersion with our sensor glove to further enhance the training feedback and to effectively foster agency while accelerating motor gains during rehabilitation.

REHAB WEEK 2021

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VIRTUAL EVENT



TOPIC: Breaking down barriers to clinical uptake of VR

An Affordable, Wearable Virtual Rehabilitation Setup

Sierotowicz, Marek, 1,2, Castellini, Claudio, 1,2

1: Friedrich Alexander University, Erlangen, Germany; 2: German Aerospace Center, Wessling, Germany

Immersion in a Virtual Reality (VR) environment has recently been proposed as a possible way to treat phantom limb pain by showing amputees an avatar of their missing limb. Most notably, sEMG-based machine learning has successfully been used to implement a VR-simulation showing an amputee a virtual hand, which can be controlled by performing muscle contractions. Such setups often use off-the-shelf hardware, which can still be relatively expensive for an average consumer, and the use of which is typically limited to a restricted space determined by optical equipment used to track the user's position in space.

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23-25 SEPTEMBER 2021
VIRTUAL EVENT



TOPIC: Virtual rehabilitation and brain-computer interface and neurofeedback

ARRoW-CP: Virtual walking rehabilitation for children with cerebral palsy. Game design framework and Preliminary results.

Guinet Anne-Laure, Bouyer, Guillaume; Otmane, Samir; Desailly, Eric

Fondation Ellen Poidatz, Research & Innovation, Saint-Fargeau-Ponthierry, France; Université Paris-Saclay, Univ Evry, IBISC Lab, Evry-Courcouronnes, France

Introduction. Serious games (SG) combined with virtual or augmented reality technologies are used to improve gait parameters for children with cerebral palsy (CP). We have developed a SG using the Microsoft Hololens augmented reality headset called ARRoW-CP, which integrates motor learning theories and audio-visual feedback to perform a 4-week intensive overground gait training (OGT) for children with CP.

Methods. This work followed the development framework PROGame within a multidisciplinary team. Regular user tests with therapists and patients were conducted to be as close as possible to their needs. Key steps of the project included: 1. A validity study of the algorithm measuring spatiotemporal gait parameters with the AR headset 2. An experimental study to determine the best combination of feedback modalities to achieve maximum walking speed (WS) 3. A randomized control trial (in progress) including children with CP. They participate in a four-week OGT with ARRoW-CP vs. treadmill training. Outcomes are the 6-minutes-walk test and the Muscle-Power-Sprint-Test, which assess functional capacity and anaerobic performance.

Results. First qualitative results (N=5) show a significant improvement for 6MWT and MPST. Enjoyment and motivation are higher in the ARRoW-CP group. Children present a linear progression in WS between each session and weeks.

Discussion and Conclusion. ARRoW-CP combines multiple ingredients of motor learning theories³: context focused therapy, goal-directed training, task-specific, variable practice, high intensity, feedback during therapy sessions and motivation of the patient. Preliminary results are very positive, we plan to include 40 patients to test our rehabilitation programme and the benefits of our SG.

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VIRTUAL EVENT



TOPIC: Virtual rehabilitation and brain-computer interface and neurofeedback

Training on an eye-controlled game: a fMRI study with a stroke patient

García-Ramos, Bárbara Rachel, García-Ramos, Bárbara Rachel; Villarroel, Rebeca; Revert, Consuelo; Marcano, Francisco; Plata-Bello, Julio; Díaz-Martín, David; González-Mora, Jose Luis; Modroño, Cristián
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Instituto de Tecnologías Biomédicas, Universidad de La Laguna, Tenerife, Spain

Instituto de Universitario de Neurociencia, Universidad de la Laguna, Tenerife, Spain

This fMRI work investigates changes in brain activity of a hemorrhagic stroke patient related to the practice on eye control of virtual objects. On the basis of our previous works in healthy subjects, we expect to find increase of activations in sensorimotor regions after a training period.

We included data of a subacute stroke patient (age=62). He was trained for four weeks in an eye-controlled version of the Matching Pairs (Memory) card game. During the training task, he had to match pairs of cards by moving a virtual cursor with his gaze. Before and after the training, he was engaged in an eye-controlled continuous tracking of a target during a functional MRI session. The experiment (pre and post test) included two conditions: tracking and fixation. Data processing was done by using SPM12 software.

The results showed an increase of activations in cortical and noncortical motor regions after the training period, including premotor cortex and cerebellum.

As we expected, the training on eye control of virtual objects was associated to increases of activity in sensorimotor regions, which extends our results from healthy volunteers to a stroke patient. This finding may be useful in the field of neurorehabilitation to create a new game-based approach to help stroke patients with limitations in the affected limbs, without resorting to limb movements.

REHAB WEEK 2021

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VIRTUAL EVENT



TOPIC: Virtual rehabilitation and brain-computer interface and neurofeedback

EEG-based Brain-Computer Interfaces and VR for Neurorehabilitation

Athanasios Vourvopoulos,

To maximize brain plasticity after stroke, a plethora of rehabilitation strategies have been explored including the use of intensive motor training, motor-imagery (MI), and motor-observation (MO). Growing evidence of the positive impact of virtual reality (VR) techniques on recovery following stroke has been shown. However, most VR tools are designed to exploit active movement, and hence patients with low level of motor control cannot fully benefit from them. Consequently, the idea of directly training the central nervous system has been promoted by utilizing MI with electroencephalography (EEG)-based brain-computer interfaces (BCIs). To date, detailed information on which VR strategies lead to successful functional recovery is still largely missing and very little is known on how to optimally integrate EEG-based BCIs and VR paradigms for stroke rehabilitation. In this presentation, we show the efficacy of EEG-based BCI-VR paradigm using a MI for post-stroke upper limb rehabilitation on functional assessments, and related changes in MI ability and brain imaging. Consistent with prior research, we found improvements in upper extremity scores (Fugl-Meyer) and identified increases in brain activation measured by fMRI that suggest neuroplastic changes in brain motor networks. This research expands on the current body of evidence, as more data are needed on the effect of this type of interventions not only on functional improvement but also on the effect of the intervention on plasticity through brain imaging.

REHAB WEEK 2021

23-25 SEPTEMBER 2021
VIRTUAL EVENT



TOPIC: Virtual rehabilitation and brain-computer interface and neurofeedback

BCI-driven functional electrical stimulation for stroke rehabilitation

Serafeim Perdakis,

Brain-computer interface (BCI)-based stroke rehabilitation has emerged in recent years as a novel and promising application of BCI that goes beyond the field's norms as an input channel for assistive technology. In this talk, after going through the basic principles and the literature of BCI-based therapies (focused on randomized clinical trials (RCT)), as well as the conclusions drawn by a recent meta-analysis of BCI-based interventions, I will present the protocol and outcomes of a recently concluded and published RCT of a BCI-actuated functional electrical stimulation (FES) intervention implemented by myself and colleagues at the Swiss Federal Institute of Technology (EPFL), under the supervision of Prof. J.d.R. Millan, and in collaboration with Swiss, German and Italian clinical partners. Specifically, I will show how this therapy has been shown to deliver clinically relevant, significantly higher than Sham and lasting recovery of upper limb functionality. Evidence will be additionally provided supporting the hypothesis that rehabilitation efficacy is fueled by cortical neuroplasticity guided by the BCI. Importantly, quantitative evaluation will be offered on the critical role of the contingency between efferent and afferent signals (ensured by the BCI component) in promoting activity-dependent plasticity and, ultimately, functional improvements. The added value of rich somatosensory feedback is also highlighted. Finally, I will discuss the implications of applying similar rehabilitation regimes with acute populations, and lay out my future plans in this line of research.

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TOPIC: VR and computational techniques to enhance rehabilitation

Motion Tracking Using AI and Standard Video for Exergaming

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Motion tracking is an essential part of exercise games, and simple, yet accurate motion capture systems are vital for implementation success. The aim of this study was to compare a deep learning (ML) method of extracting joint center positions from standard digital video (DV) camera data with data from a depth-sensing camera and the gold-standard 3DMoCap data. Twelve older adults played a custom exergame while a depth-sensing camera (Kinect), a DV camera (GoPro), and a four-camera 3DMoCap system (Qualisys) captured their movements. A DL system (DeepLabCut, DLC) was used to extract joint center positions from the DV images. Segment length variability (mean standard deviation (SD)) was used to compare systems. The DLC and 3DMoCap segment length variability difference between systems was not statistically significant for some segments. This was also true for the comparison between DLC and Kinect, and Kinect and 3DMoCap. Overall, the DLC system performed at a level comparable to either 3DMoCap or Kinect. These results show that a DL-based motion capture system can achieve measurement stability in segment lengths that were comparable to a Kinect camera, and in some segments even to the gold-standard 3DMoCap segment lengths.

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Multi-sensory feedback for upper-extremity myoelectric control

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Introduction and Aims: Following neurotrauma, rehabilitation to restore functional independence of upper-extremities or to improve myoelectric device control is a time-intensive process. We aim to accelerate the rehabilitation process by providing enhanced multi-sensory feedback within an immersive virtual reality (VR) environment for training muscle control.

Methods: Unique combinations of visual feedback (VF) and vibrotactile feedback (VTF) were provided in real-time during isometric muscle training within a VR environment. Three able-bodied participants donned a restrictive brace and virtual headset to control an upper-extremity virtual prosthetic by the mapping of isometric electromyography activity to direction intent. Participants completed reaching tasks during pre-test, training, and post-test sessions with sensory feedback provided only during training sessions. VF was provided in various levels of complexity (simple versus complex) and intermittency (continuous versus bandwidth) as a projection of the participant's virtual position to the shortest path length. VTF was provided in either simple or complex modes and was coupled to position error in conjunction with bandwidth VF.

Results: During training sessions, bandwidth VF leads to significantly faster completion times and shorter total path lengths compared to continuous VF. Bandwidth VF also resulted in a higher total variance explained in the first principal component of electromyography activity.

Discussion and Conclusion: Our objective was to develop a novel rehabilitation platform that utilizes multi-sensory feedback to optimize myoelectric control after neuromuscular trauma. We determined that bandwidth VF has potential to outperform continuous VF during training sessions for improving muscle control within VR environments.

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TOPIC: VR and computational techniques to enhance rehabilitation

3D Body Landmark Detection for Movement Tracking in VR Rehabilitation

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Introduction and aims: Head-mounted VR devices have shown promise in rehabilitation by enabling pain mitigation strategies, encouraging physical activity, and altering behavior. However, VR immersion is often constrained to hand and head gestures - excluding lower body segments from rehabilitation - and has limited ability to provide quantitative movement outcomes through solutions such as pose estimation that fit approximated body models with limited accuracy. To overcome these limitations, we have developed an alternative 3D Body Landmark Tracking approach that enables accurate whole-body tracking by directly localizing and tracking body landmarks with a single RGB-D depth-sensing camera.

Methods: 10 healthy participants (5F/5M; 21-31 years) performed common post-injury rehabilitation activities including gait, lateral/forward reach, finger/toe tapping, and head movement at 3 self-selected speeds. The point-cloud data recorded with the RGB-D camera (Kinect Azure) were processed through a multi-stage algorithm architecture including background removal, body segment identification and 3D landmark extraction. Spatiotemporal gait and targeted limb movement outcomes were compared to a gold-standard motion-capture system (Vicon) via two-way mixed-effects intraclass correlation coefficients (ICC) for absolute agreement.

Results: Our algorithms achieved $ICC=0.97\pm0.02$ with respect to Vicon across all fine-motor and whole-body movement outcomes, which was 30% greater than traditional Kinect pose estimation ($ICC=0.76\pm0.24$)

Discussion and conclusion: Our study demonstrates the feasibility of obtaining accurate movement tracking measures for head, upper- and lower-limb activities used in rehabilitation. The 3D Body Landmark

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Tracking algorithms surpassed current pose estimation for accuracy and hold promise for more robust rehabilitation assessments during exercise when integrated into a VR environment.

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Using Pose Estimation and Machine Learning to predict Fugl-Meyer and Balance Test scores in patients

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In this study we introduce an objective, computational mechanism, that automates the assessment of motor tasks performed by patients, in diagnostic testing scenarios or in rehabilitation programs. The system allows easy, non-invasive, and accessible assessment and is based on a novel multi depth-camera human motion tracking system developed by the authors. Using the data extracted from the cameras, machine learning classifiers were developed to evaluate the performance of the tasks by the patient. The approach was implemented on the Fugl-Meyer and Berg Balance Scale diagnostic tests where test scores were predicted. Additionally, we use machine learning tools to increase efficiency of testing when a battery of motor tasks are involved in the diagnosis. The machine learning based system is an adaptive scheme, that selects a sequence of motor tasks per individual dependent on the scores he/she receives on these tasks and predicts the final diagnostic score. The number of motor tasks required to predict the final score of the diagnostic test is greatly reduced without compromising the quality and accuracy of the diagnostic score. The method was implemented on the Berg Balance Scale reducing the number of BBS tasks required to assess fall risk from 14 tasks to 4-6 tasks per individual while maintaining an accuracy of 96-97%. The approach and methods presented in this talk are easily transferable to other tests and programs that involve a sequence of motor tasks.

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Dynamic personalization of virtual games: A tool to enhance rehabilitation for children with cerebral palsy

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Personalized virtual games (PVG) aim to address the changing abilities of clients by adjusting the difficulty of the activity relative to an individual's current abilities and to changes in performance due to improvement (e.g., driven by the therapeutic intervention) or to any deterioration as may occur (e.g., due to fatigue). The goal of this presentation is to summarize the development and evaluation of a PVG for rehabilitation of children with cerebral palsy (CP). Sixty typically developing (TD) children, aged 6-10 years and 20 children with CP, aged 7-11 years, participated in a single 50-minute session where they played the game in conventional and personalized modes (accuracy, dwell and weights for the TD group). Comparisons between the two modes for the TD group showed that they exerted significantly more effort while playing the PVG although there were no significant differences in enjoyment. In contrast, for children with CP, no significant differences were found between conventional and personalized games for all tested variables. When the PVG was played without weights, percent success was significantly higher for the TD group, and movement duration was significantly longer. In contrast, no significant differences in performance or any of the kinematic variables were found between the TD group with weights and the CP group without weights. Study results suggest that the PVG provides challenges that encourage participants to exert greater effort while preserving a high level of enjoyment. The availability of a PVG may allow clinicians to be more available and attentive to the client and provide therapy at just the right level of challenge to encourage motivation and engagement.

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TOPIC: VR and computational techniques to enhance rehabilitation

Validating Machine Learning for classifying individuals with Concussion using VR-based Posturography and Clinical Assessments

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Concussion has a high prevalence among athletes of all ages and the incidence rate has been rising over the past 10 years. Current diagnosis relies on assessing numerous signs and symptoms, such as vestibular/balance, visual/oculomotor, and cognitive signs, and headache, nausea, fatigue, and dizziness symptoms. The purpose of this study was to evaluate the ability of different machine learning (ML) approaches to classify concussed versus non-concussed using posturographical data and clinical data from oculomotor assessments and medical history. The ML approaches included Random Forest, Multilayer Perceptron, and Adaptive Boost, which were iterated many times to determine statistically important features. We also aimed to evaluate concurrent validity of postural assessments by comparing a novel virtual reality (VR) assessment to the gold-standard Sensory Organization Test. This was a secondary analysis on data we previously collected, which included 86 college students (Concussion/Healthy=27/59; M/F = 53/33). Results revealed ML algorithms show promise in distinguishing healthy versus concussed individuals and were able to synthesize multiple posturographical and oculomotor tests. Specifically, a 6 - 11% increase in mean accuracy compared to the null hypothesis was found and as high as 0.94 specificity, which was more accurate than traditional statistical analyses (logistic regression, ROC curve). Important features identified in the ML approaches included concussion history, near point of convergence, and postural tests with visual-vestibular conflict. Furthermore, the VR postural conditions were found to have higher importance than the SOT postural conditions. This study provides evidence that simple ML models can achieve high specificity using standard clinical tests and VR-based posturographical data, attaining up to 80% accuracy and 94% specificity, with a very small dataset by ML standards. With a larger training set, these models can help guide clinical decision-making by utilizing multiple objective, cost-effective measures working in concert.