Title: Long Pulse Width Electrical Stimulation (LPWS) Exercise and Denervation after Spinal Cord Injury-Part 1

Authors: Ashraf S. Gorgey and Ines Bersch-Porada

Historically, persons with SCI with lower motor neuron injury would not benefit from standard neuromuscular electrical stimulation (NMES). Unlike NMES, the use of long pulse width electrical stimulation (LPWS) protocol provides the use of long pulse duration that may extend from 35-300 ms. The European project, Research and Innovation Staff Exchange (RISE) successfully restored 24% of the trained knee extensor CSA following application of functional electrical cycling (FES) with LPWS (120-150 ms) at amplitude of 250 mA for 5 days per week. Denervated muscles in persons with SCI experience severe atrophy with transformation of muscular tissue into fibrous connective tissue and infiltration of intramuscular fat (IMF). Compared to persons with upper motor neuron SCI, skeletal muscle is 40-60% smaller with excessive IMF that may exceed 15%. This is typically associated with loss in bone mineral density of the distal femur and proximal tibia. We will discuss 1) effects of lower motor neuron injury on muscle size, cardiometabolic profile and bone mineral density in persons with SCI. We will also discuss recent findings 2) regarding utilizing LPWS electrical stimulation exercise to overcome the effects of denervation on the paralyzed muscles in persons with SCI. The presentation will highlight the preliminary finding from a concluded clinical trial about the effects of 12 months of LPWS in conjunction with testosterone treatment on muscle size, body composition and other cardio-metabolic risk factors compared to standard NMES and testosterone treatment. The preliminary results highlight the need for more studies to determine the most effective stimulation protocol as far as the training frequency and the stimulation parameters necessary to develop muscle hypertrophy and attenuate cardio-metabolic risk factors in this subpopulation with SCI.

Keywords: Long pulse width electrical stimulation, Lower motor neuron injury, Denervation, SCI

Long Pulse Width Electrical Stimulation (LPWS) Exercise and Denervation after Spinal Cord Injury-Part 2

Authors: Ashraf S. Gorgey and Ines Bersch-Porada

Historically, persons with SCI with lower motor neuron injury would not benefit from standard neuromuscular electrical stimulation (NMES). Unlike NMES, the use of long pulse width electrical stimulation (LPWS) protocol provides the use of long pulse duration that may extend from 35-300 ms. The European project, Research and Innovation Staff Exchange (RISE) successfully restored 24% of the trained knee extensor CSA following application of functional electrical cycling (FES) with LPWS (120-150 ms) at amplitude of 250 mA for 5 days per week. Denervated muscles in persons with SCI experience severe atrophy with transformation of muscular tissue into fibrous connective tissue and infiltration of intramuscular fat (IMF). The methodology for the diagnosis of damage to the lower motor neuron in muscles of the upper and lower extremities through the use of electrical stimulation (Motorpoint integrity testing) is still not practically acceptable. Following denervation, several hand disorders have been identified that are likely to impact the progress of the intervention. The potential deficits that may result from partial or complete denervation of muscles will be also discussed, with particular attention paid to their impact on the functionality of the affected muscles and neighboring muscles. Based on studies conducted by the International FES Centre®, stimulation protocols will be presented that demonstrate effectiveness. The presentation will also address the risks and precautions associated with the use of these protocols, and video examples will illustrate the feasibility of implementing long pulse width stimulation. The primary objective of the second presentation is to identify the most current hand disorders after SCI and how likely to utilize electrical stimulation as a potential diagnostic tool to distinguish denervated muscles from innervated muscles. The authors will provide details on the placement of the electrodes and the stimulation parameters that likely to enhance activation of the muscles following denervation. Finally, the audience will develop skills to use electrical stimulation exercise to train denervated muscles in both upper and lower extremities after SCI.

Keywords: Long pulse width electrical stimulation, Denervation, hand deformities diagnostic tool, SCI

Ultrasound Imaging on Myofascial Trigger Points for Investigating Effects of Electrical Muscle Stimulation with Self-Stretching on Upper Back Pain.

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Introduction: Myofascial trigger points (MTPs) are a major cause of upper back pain, especially in the upper trapezius muscle (TM). MTPs, identified as irritable nodules within taut bands, can appear as band-like hypoechoic regions on ultrasound imaging when inflamed and containing trapped fluids, causing pain [1]. Numerous methods exist for releasing MTPs, including trigger point pressure release (TPR). Downward compression of the MTP stretches sarcomeres and alleviates pain. Prior work has demonstrated that combined electrical muscle stimulation (EMS) and self-stretching (SS) also offers immediate pain relief [2]. This study used ultrasound imaging to compare the effects of EMS+SS and TPR on upper TM morphology and evaluate treatment effectiveness through acute changes in muscle characteristics.

Methods: Two electrodes were placed across the muscle line on the side opposite to the MTP location, creating active resistance during the individual's self-stretching of the upper TM. A pilot study using B-mode ultrasound imaging examined eight participants with MTPs located in the upper TM with ethical approval [3]. Three images were captured on both sides of the upper TM, with and without the presence of MTPs. Changes in MTP size, echo intensity (EI) within the MTP, TM thickness at rest and during stretching, and range of motion (ROM) were analysed using Image J analysis software. These values were averaged and compared between pre-and post-treatment for both EMS+SS and TPR.TPR involved applying pressure with the thumb directly to the MTP at the upper TM to the maximum tolerated level. The EMS protocol employed biphasic square pulses with constant current mode, a 20 Hz stimulation frequency, 100 μs pulse width, and an amplitude adjusted to an acceptable level (Fig. 1). Each treatment session consisted of three sets of ten-second stimulations alternated with ten-second rest periods. A paired t-test was analysed for changes at pre- and post-therapy and compared between EMS+SS and TPR.

Results: Eight participants (four males and four females), with a mean age of 30.50 ± 3.78 years and a normal BMI of 21.80 ± 2.05 kg/m², were enrolled in this study. EMS+SS significantly improved ROM ($t_{(7)} = 3.286$, $p = .013$) and reduced MTP size ($t_{(7)} = -4.034$, $p = .005$). Similarly, TPR significantly improved ROM ($t_{(7)} = 4.203$, $p = .004$) and reduced MTP size ($t_{(7)} = -5.293$, $p = .001$). There were no significant differences in changes in ROM, MTP size, EI within the MTP, and TM thickness at rest and during stretching when comparing EMS+SS to TPR treatment (Tab1).

Discussion and conclusion: This study focused on the immediate effects of the treatment. EMS+SS significantly and immediately improved ROM and reduced MTP size, showing effectiveness comparable to TPR. EMS facilitates TM stretching and breaks down adhesions within the MTP, reducing MTP size. Both EMS+SS and TPR improve blood circulation, promote tissue healing, relax muscles, and enhance muscle lengthening. Although sarcomeres revert to their original shape after muscle release [4], ongoing treatment and proper posture are crucial to prevent MTP progression.

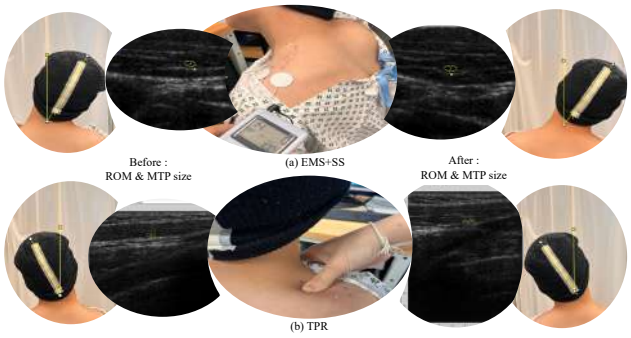


Figure 1: Pre- and post-treatment ROM and MTP size (ultrasound) for (a) EMS+SS and (b) TPR in participants with trapezius MTPs.

Table 1: Changes in ROM, MTPs size, EI at the MTP, and TM thickness at rest and during stretching between before and after EMS+SS and TPR treatments (*$p < .05$, **$p < .01$).

Task	EMS+SS		TPR	
	MEAN±SE	t-value	MEAN±SE	t-value
ΔROM	5.89±1.80	3.286*	6.11±1.45	4.203**
ΔMTP_size	-0.83±0.21	-4.034**	0.82±0.16	-5.293**
ΔEI at MTP	0.57±1.93	0.297	-0.74±2.05	-0.362
ΔTM_thickness at rest	-0.04±0.29	-0.123	0.20±0.31	-0.658
ΔTM_thickness duringstretch	-0.11±0.33	-0.334	-0.30±0.37	-0.823

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NEUROMUSCULAR INEFFICIENCY IMPAIRS MUSCLE PERFORMANCE IN HOSPITALIZED PATIENTS: A FES CYCLING-BASED EVALUATION METHOD OBSERVATIONAL STUDY

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Introduction: Functional electrical stimulation cycling-based evaluation is a safe and feasible muscular assessment method for hospitalized patients [1]. The aim of this study was to investigate a possible relationship between neuromuscular efficiency and muscle performance in hospitalized patients through a FES cycling-based evaluation method.
Methods: This is a retrospective observational study. Data from 49 hospitalized patients with clinical sings of muscle weakness were analysed. During the functional electrical stimulation cycling-based muscular evaluation, the equipment was set in the evaluation mode to perform an automatic preset combination of different cycle ergometry cadences (10, 15 and 20 RPM) and electrical stimulation frequencies (50, 75 and 100 Hz) maintaining a previously selected pulse width and intensity throughout the evaluation protocol [2]. The patients did not undertake any voluntary effort. All the work was performed by the FES-cycling equipment. The equipment assessed the muscle performance by the maximum torque and power output achieved. The neuromuscular efficiency was assessed by the stimulation cost (defined as the electrical charge delivery rate per watt of output power [microcoulomb/watt - μC/W]). Previously published data [2] from healthy subjects were used as reference to state low or normal muscle performance and neuromuscular efficiency. Data normality was assessed by the Shapiro-Wilk test. The Spearman test was used to assess the correlation between neuromuscular efficiency and muscle performance. A multiple linear regression was used to stablish the association between neuromuscular efficiency and muscle performance. The Fisher's exact test was used to analyze the difference in percentage of patients with normal/low neuromuscular efficiency and muscle performance.
Results: The patients and FES-cycling evaluation basic characteristics are presented in table 1. There was a negative correlation between stimulation cost and torque ($r = -0.72$, $p < 0.0001$) and power output ($r = -0.87$, $p < 0.0001$). There was an association between torque and neuromuscular efficiency ($R^2 = 0.29$, β for age = 0.02, SE = 0.02, $p = 0.4962$ and β for stimulation cost = - 5.68, SE = 1.35, $p = 0.0001$). There was an association between power output and neuromuscular efficiency ($R^2 = 0.37$, β for age = -0.01, SE = 0.03, $p = 0.7484$ and β for stimulation cost = - 7.92, SE = 1.69, $p < 0.0001$). Figure 1 presents the difference of patients with normal/low neuromuscular efficiency and muscle performance. In patients with low neuromuscular efficiency, 91% presented low torque and 9% presented normal torque ($p = 0.0019$). In patients with normal neuromuscular efficiency, 0% presented low torque and 100% presented normal torque ($p = 0.0019$). In patients with low neuromuscular efficiency, 72% presented low power output and 28% presented normal power output ($p = 0.0304$). In patients with normal neuromuscular efficiency, 0% presented low power output and 100% presented normal power output ($p = 0.0304$).
Discussion and conclusion: There is a relationship between neuromuscular efficiency and muscle performance. Low neuromuscular efficiency impairs muscle performance in hospitalized patients.

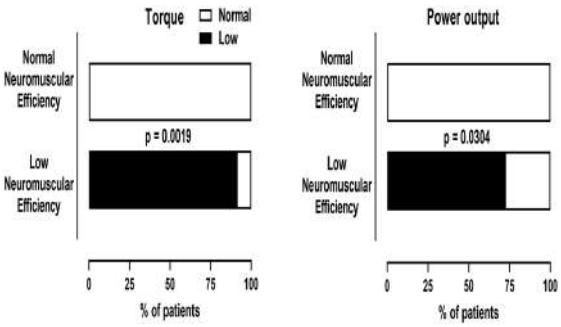


Figure **1**: Percentage of patients with normal/low neuromuscular efficiency and muscle performance.

Table 1: Patients and evaluation basic characteristics.

Variable	
Age (years)	63 ± 15
Gender (M/F)	27/22
Intensive Care Unit patients (%)	61
Ward patients (%)	39
Pulse intensity (mA)	100 [65-130]
Pulse width (μs)	500 [500 – 600]
Torque (Nm)	3.21 [2.09 – 4.72]
Power output (W)	5.95 [2.89 – 6.91]
Stimulation cost (μC/W x 10^3)	9.48 [4.88 – 23.74]

mA, milliamps; Nm, Newton meter; W, Watts; μC/W, microcoulombs per watt. Data are presented as means ± standard deviation and median [interquartile range].

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TENS Evoked Sensory Percepts Enable Slip Warning and Prevention during Prosthetic Grasps

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Introduction: Object slips may occur during prosthetic grasps. Often prosthetic users rely on visual feedback to monitor the entire process of grasping. Providing natural slip awareness to users is still not well resolved[1]. This study evaluates a novel way to evoke a slip sensory warning for subjects with upper limb loss using transcutaneous electrical nerve stimulation (TENS)[2], [3]. The sensory warning allows the subject to use voluntary actions to stop the slip. The slip prevention could also be accelerated using reflex adjustment of grasp forces. Results demonstrate the effectiveness of this approach, in which the subject plays a master role in coordinating sensorimotor responses.
Methods: TENS was programmed to elicit multiple percepts at the skin of subjects[3]. A biomimetic slip sensor was used to sense the shear force (or friction force) at the prosthetic fingertip. It then triggered a change in electrical stimulation parameters in frequency and amplitude. This elicited a vibration feeling at the skin over the background stimulation that was tuned to create a buzz feeling correlating to contact force. The change in sensory modes allowed subjects to perceive slip occurrence. They were instructed to increase grasp force voluntarily upon detecting a transition from buzz sensation to vibration sensation. This closed-loop voluntary response was tested in 5 able-bodied subjects and 2 subjects with amputation for its effectiveness.
Results: Psychophysical test for perception revealed that the slip event can be detected effectively with a success accuracy of 96.57%. The threshold of slip or friction force was proportional to that of perpendicular grasping force. In a slip prevention test, all subjects showed the ability to stop object slipping with volitional responses to the sensory warning. Furthermore, reflex compensation yielded faster increase in grasp force than the voluntary action alone. On the average, the responses were characterized with a median response time of 0.30 (0.08) s, a rise time of 0.26 (0.03) s, an execution time of 0.56 (0.07) s, and a slip distance of 0.39 (0.10) cm. Prosthetic grip force was found highly correlated to that of an intact hand with a correlation coefficient of 96.85% (2.73%).
Discussion and conclusion: Results show that it is feasible to reconstruct closed-loop biomimetic sensorimotor pathways to ensure stable grasps by prosthetic users. The electrical stimulation of sensory percepts allows for enhanced bi-directional human-prosthetic interactions.

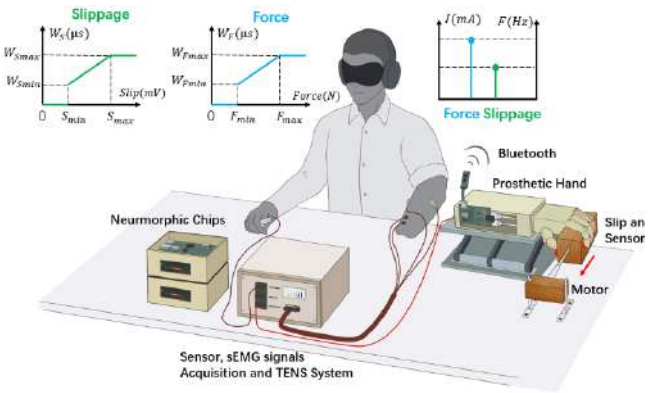


Figure **1**: Biomimetic prosthetic hand for slip prevention.

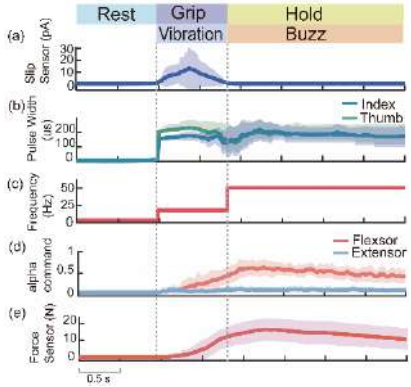


Figure **2**: Voluntary response in an amputee.

Acknowledgments: In case acknowledgments are included, the paragraph must be placed before the bibliography.

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NON-INVASIVELY EVOKED TACTILE SENSATION VIA TENS PROVIDES VERSATILE SENSORY FUNCTIONS FOR PROSTHETIC USERS

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Introduction:
Lack of feeling to prosthetic hands remains the greatest barrier to prosthetic users. Recent advances in neural interface technologies have restored some degree of sensory ability [1]. However, providing sensory functions with non-invasive means is still considered primitive, although electrotactile or vibrotactile techniques have long been examined. The critical issues with sensory neural interfaces are somatotopic specificity, perceptual qualities, stability and longevity. In our studies, we demonstrated that somatotopically specific and stable hand digit sensation can be obtained in certain population of subjects with upper limb loss. We characterized this phenomenon as evoked tactile sensation (ETS) using transcutaneous electrical nerve stimulation (TENS) [2], and applied this technique to inform grasp force in prosthetic hands for those subjects with ETS [3]. Here, we report that the non-invasive ETS can allow restoration of other sensory functions with its traits of digit precision and multiple sensory percepts.
Methods: Figure 1 depicted the experimental setup and methods. The projected finger map (PFM) areas in the skin of forearm stump of subjects with transradial amputation were identified. Ag/AgCl powder sintered electrodes of 10 mm diameter were placed on the PFM areas of individual fingers. Biphasic, regulated current square pulses were delivered to the electrodes to elicit different sensory percepts, ranging from touch, pressure, vibration, buzz, numbness to tingling pain with increasing charge injection. Amplitudes and frequencies were incrementally fixed at each sensory mode, while pulse width was varied to modulate the sensory intensity. Force sensor, temperature sensor and slip sensor were placed at the tip of prosthetic fingers to monitor physical conditions. Electromyographic (EMG) signals were recorded from stump wrist flexor and extensor muscles to control the opening and close of prosthetic hands. Interference from TENS to EMG was removed with a hardware/software filtering technique. Five able-bodied subjects and six subjects with transradial amputation were recruited to test different sensory functions.
Results: Among the sensory percepts, buzz sense had the widest range of pulse width modulation, thus it was chosen to encode grasp force at the fingertip. Tingling pain was elicited at high stimulation amplitude/frequency, and could be used to signify hazard conditions, such as high temperature. Vibration was a distinctive type of sensation, and was used to inform slip occurrence during grasps. Test results demonstrated the versatile functionality provided by the ETS feedback. Specifically, with force feedback in buzz mode, subjects were able to identify object size and compliance simultaneously. With temperature monitoring, when the temperature of object reached to the hazard threshold, subjects were able to feel the tingling pain sensation and to release the object immediately to prevent potential damage. With the slip sensor, a slip event triggered a change in stimulation parameters to elicit a vibration sensation. Subjects were able to recognize this change in sensory modes and take necessary precautions to stop the slip effectively.
Discussion and conclusion: Studies have confirmed that the non-invasive ETS by TENS is capable of generating multiple sensory percepts that afford versatile sensory functions for prosthetic users.

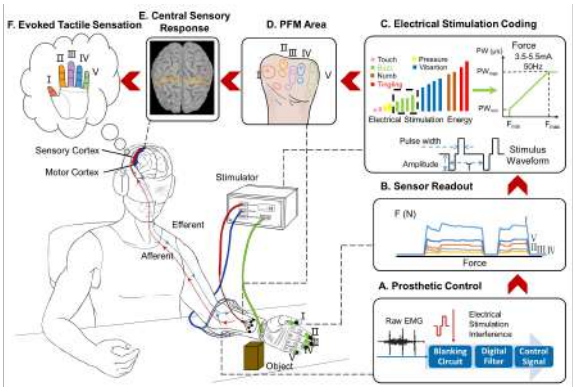


Figure **1**: ETS sensory feedback system and experiment setup.

Acknowledgments: The authors would like to thank all subjects for their participation in this study.

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DEVELOPMENT OF A MULTI-FUNCTIONAL HYBRID ARM-LEG FES TRICYCLE WITH BIOFEEDBACK

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Introduction: Hybrid arm and leg FES cycling, compared to FES cycling using only the lower limbs, offers greater cardiovascular and metabolic benefits for individuals with SCI [1] and enhances neuroplasticity due to the simultaneous activation of the upper and lower limbs [2]. During cycling with FES, stimulation intensity can be adjusted using an external device, mostly ignoring users' voluntary intentions [3]. However, the involvement of patients' voluntary effort is crucial to enhancing neuroplasticity [4], [5]. Some studies explored a model that uses EMG signals from arm muscles to control the electrical stimulation of lower limb muscles during hybrid arm and leg cycling [6]. Our work aimed to develop a mobile rehabilitation tricycle combining arm-leg power with motor assist and equipped with an FES module for individuals with SCI, featuring adaptive stimulation intensity based on arm force input.

Methods: A powered tricycle (GoTryke, GBY SA, Switzerland) was used as the arm-leg cycling platform. The enhanced system utilises a microcontroller (Raspberry Pi 4) to gather sensor data from multiple points (such as tangential force, position, and angular velocity) via Bluetooth (Figure 1. System Overview). Data is processed to adjust stimulation parameters in real-time, tailored to the user's effort, which is measured from arm power pedals. Control is facilitated through a mobile application, enabling user-adjusted parameters such as stimulation angle range and baseline intensity. Collected data can be analysed through a cloud-based platform, providing interactive reports for both user and medical expert evaluation.

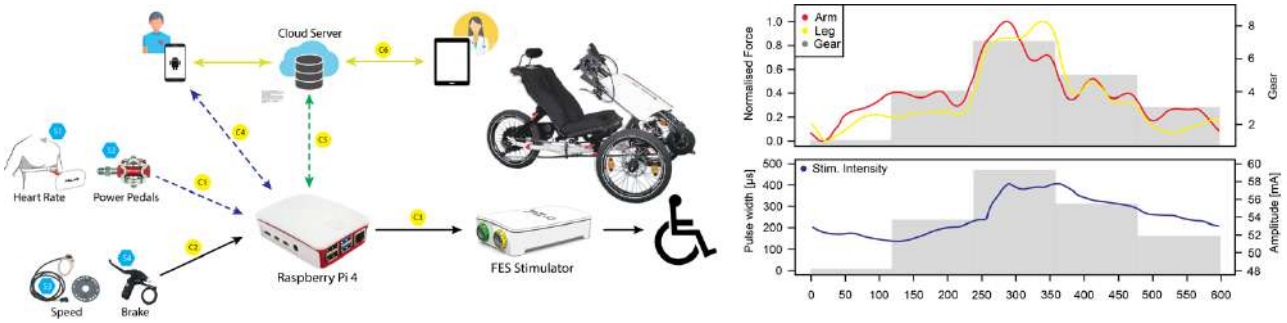


Figure 1. System Overview (left), Normalized Arm and leg forces during cycling with FES (right).

Results: This work successfully developed a fully functional rehabilitation tricycle with arm-leg propulsion and integrated FES. Performance tests involving a participant with SCI were conducted to evaluate the closed-loop control methods. The experiments analysed stimulation parameters in relation to arm and leg force values (Figure 1. System Overview). Results indicate that the biofeedback controller effectively adjusts the stimulation amplitude to increase intensity when higher power is needed, with pulse width modulating in response to resistance levels. Minor irregularities were observed only in the lowest gear settings. Field tests demonstrated the system's effectiveness, including biofeedback control and user comfort. Preliminary studies on individuals with SCI showed enhanced engagement and physical exertion during use. A cloud server infrastructure was implemented, ensuring secure data storage and analysis, with options for real-time monitoring and feedback.

Discussion and conclusion: The tricycle system significantly contributes to SCI rehabilitation by enabling regular physical activity with minimal assistance. Future developments include additional pilot testing and system refinements to optimize user experience. This project underscores the value of interdisciplinary collaboration in developing assistive technology, with the potential for broader applications in rehabilitation environments.

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Lower-limb Muscle Selectivity & Force Production of a Neural Cuff Electrode for Sciatic Nerve Stimulation

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Introduction: The ability to selectively activate specific nerve fibers is crucial for optimizing the outcomes of peripheral stimulation to restore motor function in individuals with neuromuscular impairments. However, achieving high selectivity in nerve stimulation remains a significant challenge. Cuff electrodes provide a promising solution by enabling varied stimulation paradigms that target specific regions of the nerve without puncturing it. This study assesses the selectivity and force production of a multi-contact Air-Ray cuff electrode on two separate sciatic nerve placements. Unlike prior studies that focused on single-mode stimulation, this work aims to evaluate the comparative efficacy of multiple paradigms in achieving selective muscle activation and enhanced force control.

Methods: Previous multi-contact electrode studies, such as [1] and [2], have investigated how alternative stimulation paradigms allow for distinct motor unit activation. Our work aims to expand on this through comparisons of multiple electrode placements along the same nerve and an assessment of muscle output using force production. This study followed an expanded version of the protocol described in [2]. Two 8-contact Air-Ray cuff electrodes (CorTec Neuro) were surgically placed at distinct locations along the sciatic nerve of an anesthetized pig. Each electrode consisted of two longer contacts (C1 and C2), used for longitudinal stimulation, and six shorter contacts (C3–C8) used during the longitudinal, nearest-neighbor (NN), and second nearest-neighbor (SNN) stimulation paradigms. In the longitudinal stimulation paradigm, either C1 or C2 was set as the anode while a shorter contact acted as the cathode. Stimulation pulses were applied at amplitudes from 80 and 800 µA with a 200 µs pulse width and a 1 Hz frequency. Each amplitude level was tested for 3 seconds, with 2 seconds between pulses. Identical stimulation parameters were applied for all paradigms. In the NN configuration, one contact was chosen as the cathode and its neighbors on either side as anodes. In the SNN configuration, contacts one position away from the cathode were chosen as the anodes. Needle electromyography (EMG) sensors were placed in the pig's soleus, tibialis cranialis, extensor digitorum brevis, and interosseus muscles, and a force transducer (mini45, ATI) was secured to the pig's hoof.

Results: Fig 1. Shows the EMG recruitment graph and force production for the longitudinal stimulation paradigm on one electrode placement. In these experiments, certain configurations yielded recruitment of individual muscles, while others engaged multiple muscles. Selectivity in muscle recruitment patterns became pronounced at higher amplitudes, but even at lower amplitudes, distinct recruitment patterns appeared. The longitudinal and NN configurations showed consistent force generation, with certain cathode contacts producing higher net force than others.

Discussion and conclusion: The variability in force production among electrode contacts further underscores the benefits of multi-contact cuff electrodes for peripheral nerve stimulation. The ability to modulate force output depending on contact selection adds an additional layer of control, enabling customized force production aligned with therapeutic goals. This fine-tuning capability is particularly valuable for patients with neuromuscular impairments, as it allows for a range of motor responses suited to different functional needs.

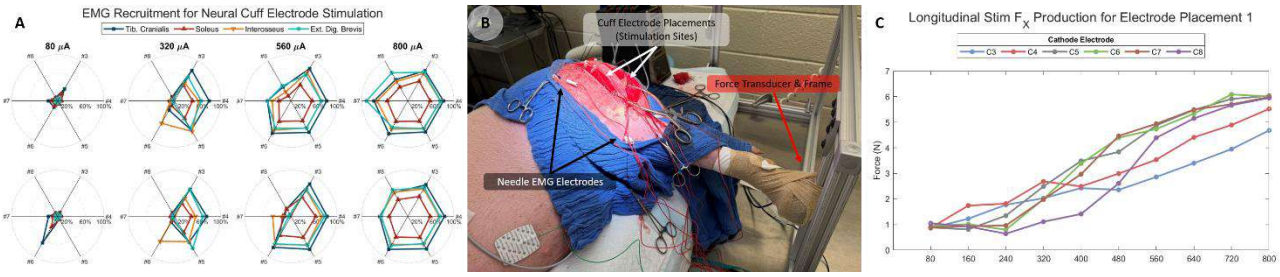


Figure 1: (A) The EMG recruitment graph for the first electrode placement for various current amplitudes. (B) A diagram of the experimental setup. (C) The F_x force production during longitudinal stimulation for the C1 anode.

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Spinal Cord Stimulator Implant Procedure for Targeting the Ventral Spinal Cord

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Introduction: Spinal cord stimulation (SCS) has been used extensively to treat chronic pain[1]. SCS is increasingly used in clinical trials for motor rehabilitation in conditions such as spinal cord injury (SCI), stroke, and Parkinson's disease[2]. Typically, SCS leads are placed on the dorsal aspect of the spinal cord (SCS_D). The mechanism behind SCS_D involves the excitation of large-diameter afferent fibers within the dorsal columns and dorsal roots, which in turn, indirectly activate motoneurons via reflexive pathways[3]. Although SCS_D has shown potential for improving motor rehabilitation, its efficacy is limited by the indirect activation of motoneurons and dispersion of electrical currents in the cerebrospinal fluid, which leads to broad muscle activation[3]. To address this, we propose stimulating the ventral aspect of the spinal cord (SCS_V), closer to the motoneurons, to increase specificity of muscle activation. Our hypothesis is supported by animal work, which showed that SCS_V can selectively activate different muscles of the rat forelimb[4]. Here, we aim to refine the traditional SCS electrode implantation technique to precisely target the ventral side of the lumbosacral spinal cord in humans.

Methods: Three SCS leads were implanted in a 35-year-old female cadaver specimen (Figure 1). The leads were inserted by two experienced physiatrists using an epidural Tuohy needle, positioned slightly laterally at an angle pointing towards the contralateral side of the spinal cord. Under live fluoroscopic guidance, the leads were maneuvered across and around the spinal cord to the ventral aspect as follows: lead 1 was inserted at the L2/3 interspace and guided to the T10 superior endplate; lead 2 was inserted at the L5/S1 interspace and guided to the L1 superior endplate; lead 3 was inserted through the sacral hiatus and guided to the L2 superior endplate. After the leads were maneuvered to their desired location, the needle was removed, and the lead wires were sutured in place to prevent movement. Computed tomography (CT) imaging and anatomical dissection were subsequently performed to confirm the positioning of the leads.



Figure 1: Fluoroscopic XR image taken during implantation of leads 1, 2, and 3.

Results: Post-implantation assessments showed that leads 1 and 2 were positioned more laterally than anticipated. Lead 2 followed a complex path, weaving above and below two spinal roots as it traversed the lateral aspect of the spinal cord. Lead 3 was successfully placed ventrally.

Discussion: The lateral positions of leads 1 and 2 indicate that minor procedural adjustments are needed to improve lead placement in future attempts. Despite these challenges, the successful ventral placement of lead 3 supports the effectiveness of our approach, and we will continue to optimize this technique in subsequent trials. These results are preliminary, and we plan to conduct two additional trials in new cadavers, with three leads each. The next trials will be performed by two additional physiatrists and one neurosurgeon. SCS_V offers a potentially more precise solution to activating muscles of the lower-limb. This more targeted approach could improve rehabilitation outcomes for patients with debilitating movement disorders and improve their quality of life.

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The Interaction Between Muscle Quality and Bone Mineral Density following two Paradigms of electrical stimulation in Spinal Cord Injury

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Introduction

Spinal cord injury (SCI) negatively impacts muscle quality and bone health. Neuromuscular electrical stimulation-resistance training (NMES-RT) has been shown to enhance muscle quality. It is unclear whether adding NMES-RT to functional electrical stimulation-lower extremity cycling (FES-LEC) may further augment muscle quality and subsequently enhance bone mineral density (BMD).

Methods

Thirty-two participants were randomized into either 12 weeks of NMES-RT followed by 12 weeks of FES-LEC (NMES-RT+FES; n=16) or 12 weeks of passive movement training (PMT) followed by 12 weeks of FES-LEC (PMT+FES; n=16). To test the hypothesis, one group received NMES-RT to induce muscle hypertrophy and subsequently muscle quality and the other group received PMT. Measurements were conducted at baseline (BL), post-interventions 1 and 2 (P1 and P2) separated evenly by 12 weeks. Left thigh muscle isometric and isokinetic torques were measured using an isokinetic dynamometer. Magnetic resonance imaging measured whole thigh and knee extensor (KE) muscle CSAs. Dual energy x-ray absorptiometry measured total and regional BMD.

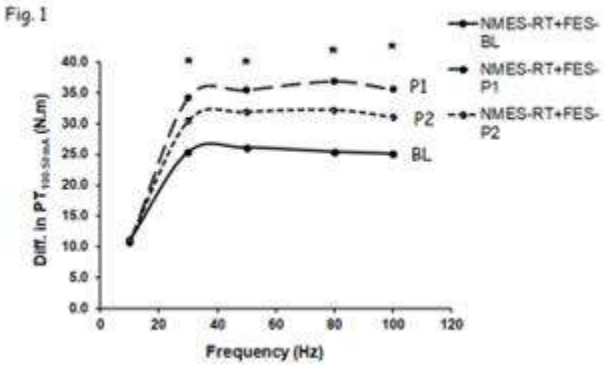


Figure 1. Diff. in isometric peak torques (Iso-PT) between 100 and 50 mA as administered at different frequencies at BL, PI and P2 in persons following NMES-RT+FES. SDs were omitted for clarity.

Results

NMES-RT elicited a trend towards greater isometric torque at 80 Hz (P = 0.057) and isokinetic torque [60 deg/sec; P = 0.009 and 180 deg/sec; P= 0.003] compared to PMT (Figure 1). Muscle CSA was greater in left whole thigh [F (2,20) =9.1; P =0.007] and KE [F (2,20) =15.5; P =0.001] by 11.0 and 8.0 cm^2 respectively at P1 in the NMES-RT+FES compared to PMT+FES. In the NMES-RT+FES, ankle weights were positively associated with muscle CSA, isometric and isokinetic torques as well as muscle quality following P1. Compared to PMT+FES, NMES-RT+FES maintained BMD at the distal femur.

Conclusion

NMES-RT+FES enhanced muscle quality as measured by torque production and muscle CSA as result of increasing ankle weights. The addition of FES-LEC to NMES-RT maintained but did not further augment muscle quality. Furthermore, NMES-RT+FES may help maintain BMD after SCI.

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Occlusion-Corrected EMG-Based Effort Estimator for FES-Assisted Rehabilitation Applications

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Introduction: Functional electrical stimulation (FES) is a widely used approach to facilitate motor recovery following a stroke by engaging paretic muscles in task practice. It aims to improve motor relearning by assisting voluntary effort during rehabilitation tasks. However, a critical challenge in FES-assisted rehabilitation is "slacking," where users rely excessively on FES assistance rather than actively engaging in the rehabilitation task. This behavior diminishes therapeutic outcomes. To address slacking, EMG-mediated FES devices use electromyography (EMG) signals to estimate voluntary effort and provide stimulation accordingly. However, current EMG-based effort estimation methods do not account for 'occlusion', a phenomenon in which the simultaneous activation of muscles through voluntary effort and stimulation reduces voluntary EMG. This leads to significant underestimation of volitional effort, compromising the estimation.
Methods: The study hypothesizes that occlusion can be quantified and corrected to enhance effort estimation accuracy. Five able-bodied participants completed isometric finger extension force tracking tasks involving combinations of voluntary and stimulation-induced muscle activation. Participants were asked to maintain a target level with their finger extension force and asked to maintain their voluntary effort when the stimulation was turned off. Occlusion is estimated as the difference as $E_o = V' - V$ as illustrated in Fig. 1. Effort estimation accuracy was compared for occlusion-corrected and uncorrected methods. Additionally, the performance of two commonly used m-Wave filters—Gram-Schmidt and comb filters—was evaluated in the context of effort estimation.
Results: Results confirmed the significant impact of occlusion correction on effort estimation accuracy. Without correction, the average effort estimation error was 17%. Occlusion correction reduced this error to -0.5%, demonstrating a marked improvement. The study also showed that occlusion increased with higher stimulation levels and decreased with higher voluntary effort, a finding consistent with prior simulations [1]. Linear regression analysis revealed that both voluntary and stimulation-induced effort levels significantly influenced occlusion, and a linear model was developed to predict the occlusion correction factor.
Discussion and conclusion: This study presents a novel occlusion-corrected effort estimation framework that enhances the accuracy of effort-dependent FES systems. By addressing the limitations of current methods, this approach promises to improve the delivery of effort-dependent FES assistance, ultimately leading to better rehabilitation outcomes. The findings underscore the importance of incorporating occlusion correction in future FES controller designs to ensure accurate effort estimation and prevent slacking. Future work will focus on validating this method with a larger sample size, including individuals with stroke in order to confirm the clinical applicability of this approach.

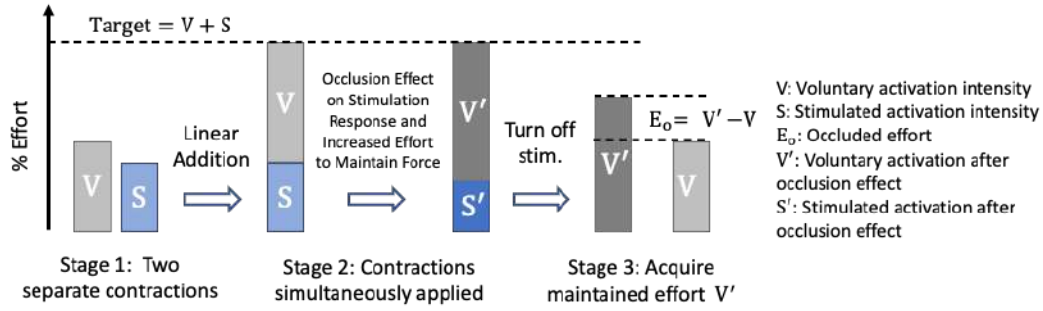


Figure 1: Illustration of the methodology used to estimate occluded effort. Participants were instructed to maintain a sub-maximal isometric force to compensate for force lost due to occlusion of both voluntary and FES activation. Turning off the stimulation made estimating voluntary effort with stimulation possible. Thus, effort lost to occlusion is calculated.

Acknowledgments: This work was supported by the National Science Foundation (grant #1942402).

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THE EFFECT OF NEUROMUSCULAR ELECTRICAL STIMULATION ON BOWEL MANAGEMENT IN PEOPLE WITH CHRONIC SPINAL CORD INJURY

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Introduction: Spinal cord injury (SCI) causes a disruption of the autonomic nervous system affecting gastrointestinal function amongst many others. More than one hour is spent for defaecation in 14% of this population imposing a severe limitation to their participation in social life activities[1] making it of superior importance in people with SCI[2]. Some people use abdominal massage just before bowel evacuation[3] whereas a combination of strategies is most commonly applied[4]. Overall, non-invasive approaches to bowel evacuation have been found to be slightly better accepted compared to implanted devices for improving bowel and bladder function and improve independence[5]. This clinical trial (NCT04914975) investigated the effect of 16 weeks of neuromuscular electrical stimulation (NMES) on the defecation time, bowel transit time, bowel and bladder function and patient satisfaction in people with chronic SCI.

Methods: Participants with SCI (A-D, C5-L3) applied home-based NMES (40Hz, 300µs, 8s on-3s off, 2s ramps) onto their abdominal musculature for 16 weeks for 30 minutes prior to their regular defaecation schedule. Bowel management was monitored for four weeks prior to and four weeks following the stimulation period. Stimulation was applied such as to produce a strong but well tolerable muscle contraction using four electrodes placed over the rectus abdominis. Five study visits spread over 24 weeks were planned to evaluate participants' bowel and bladder function by application of the Neurogenic Bowel Dysfunction Score (NBDS) and the Qualiveen Short Form (SF) respectively. Stimulation and defaecation time as well as the frequency were documented in an online database. To estimate bowel transit time, participants performed the "corn test" reporting timepoints of corn ingestion and defecation.

Results: 20 participants with chronic SCI (>2 years) were included in the data analysis. Even though the NBDS remained moderate - severe (14+) over the course of the study, the subjectively rated satisfaction with bowel management increased by two points on a 10-point Likert scale when applying NMES. Bowel transit time could be significantly reduced by 30.15 hours ($p=0.046$) after 16 weeks of stimulation. The average defecation time could be reduced by 7.32 minutes ($p<0.001$) within 8 weeks of stimulation, returning to an average baseline of 57 minutes. The Qualiveen overall score was decreased by a statistically and clinically non-significant extent (0.4 points, $p>0.05$).

Discussion and conclusion: This study showed a significant effect of NMES on bowel transit time as well as defecation time in people with chronic SCI. Despite relatively large standard deviation values observed among the results, the data were statistically significant and most importantly clinically relevant. Many of the study participants continued to stimulate their abdominal muscles after concluding their participation as the effect of NMES was not sustained after stopping stimulation. Transcutaneous NMES administered on the abdominal wall could possibly help to stimulate the gastrointestinal system non-invasively and has been shown to speed up bowel transit time in previous work[6]. The optimal dose of NMES should be investigated in future research projects.

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IMPROVEMENT OF MANUAL MOTOR ABILITY THROUGH VIRTUAL REALITY, SELECTIVE AND TRADITIONAL FUNCTIONAL ELECTRICAL STIMULATION: A RANDOMIZED CONTROLLED TRIAL

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Introduction: Functional electrical stimulation (FES) and virtual reality (VR) have emerged as effective interventions in the rehabilitation of motor function in persons with neurological diseases. FES, through controlled electrical impulses, activates specific muscles in combination with functional actions, aiding in strength recovery and improved motor coordination [1]. VR, by creating immersive and interactive environments, engages patients in targeted tasks that encourage active participation and enhance coordination [2]. Evidence supports the role of both FES and VR in promoting physical improvements, notably in grip strength and manual dexterity, making them valuable tools in advancing functional recovery in neurorehabilitation [3].
Objective: The objective of this study is to compare the improvements in manual dexterity obtained using VR, traditional FES and selective FES based on multi-field electrodes in people without neurological pathologies.
Methods: This randomized controlled clinical trial, with four distinct groups, involved 80 healthy university students and employed blinded assessments by an independent third party. The participants were divided into four experimental branches: control (no intervention), selective FES (Fesia Grasp), traditional FES (Globus Elite), and VR (Leap Motion® sensor). Each group underwent five consecutive daily sessions of 30 minutes. The intervention was in non-dominant forearm. During the 30-minute training sessions, participants underwent different interventions based on their assigned group. The selective FES group completed 5 sessions combining selective forearm muscle contractions and functional task training, progressing from isolated muscle activation (sessions 1-3) to grasping objects (sessions 4-5). The traditional FES group also had 5 sessions (15 minutes for flexors and 15 minutes for extensors), initially focusing on repetitive contractions and later on functional tasks. The VR group engaged in fine motor skill exercises using Leap Motion® in a structured gaming session, while the Control group received no intervention. In the selective FES group, multi-field electrodes allowed precise activation of specific muscle groups. The traditional FES group used traditional stimulation, applying it separately to flexors and extensors. Parameters for both groups included 25 Hz frequency, 250 µs pulse width, and intensity 5 mA above the motor threshold. Evaluations were performed at three stages: baseline, immediately after the intervention, and during a follow-up session. Manual dexterity was measured through the Nine Hole Peg Test and the Box and Blocks Test. To evaluate differences between groups over time, statistical analysis included nonparametric tests (Kruskal-Wallis) because data did not meet normality assumptions. Registered on clinicaltrials.com, ID: NCT06109025.
Results: The means of the four groups were compared to measure manipulative dexterity through the Box and Block and Nine Hole Peg Test. On the one hand, the results of the Box and Block test showed significant differences between the Control group and the traditional FES group (p=0.004) as well as selective FES group (p=0.007), indicating that the interventions with traditional FES and selective FES significantly improve manipulative dexterity compared to the Control group. No significant differences were observed among the other groups. On the other hand, the results of the Nine Hole Peg Test did not show significant differences in any group, suggesting that the evaluated interventions did not have a considerable impact on this specific measure of manipulative dexterity.
Discussion and conclusion: Even though it is a sample of healthy subjects, and the intervention is very short, the results reveal that FES is an intervention with better results to date than VR. However, more work is needed to identify which of the two FES, traditional or selective, provides the best benefits in manual motor ability.

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COMBINED FUNCTIONAL AND NEUROMUSCULAR ELECTRICAL STIMULATION FOR UPPER LIMB REHABILITATION IN HEMIPLEGIA: A CASE STUDY

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Introduction: Hemiplegia and upper limb dysfunction are among the most disabling consequences of stroke, significantly limiting independence and reducing quality of life [1]. Functional electrical stimulation (FES) facilitates voluntary movement by activating muscles through electrical impulses, thereby improving motor function in individuals with neurological conditions [2]. Similarly, neuromuscular electrical stimulation (NMES) has proven effective in enhancing both gross motor activity and activities of daily living in stroke rehabilitation [3]. The combination of FES and NMES may offer a synergistic approach to rehabilitating a hemiplegic arm, addressing both fine and gross motor skills.
Objective: This case report aims to describe the effects of a combined FES and NMES protocol on upper limb function in a patient recovering from a brain aneurysm.
Methods: A personalized rehabilitation protocol was designed for the hemiplegic arm, incorporating FES to facilitate hand and wrist movements using Fesia Grasp (Fesia Technology, Donostia-San Sebastián, Spain) and NMES applied to proximal joints with the Chattanooga Physio system (Chattanooga, California, USA). The protocol targeted the following movements: hand opening and grasping, wrist flexion and extension, elbow flexion and extension, forearm supination, and shoulder abduction. The intervention consisted of three weekly sessions, each lasting two hours, for a total duration of three months. Evaluations were conducted at baseline, during follow-up, and post-intervention using the following assessment tools: Rivermead Motor Assessment scale (RMA), Fugl-Meyer Assessment for the upper extremity (FMA-UE), Modified Ashworth Scale (MAS) for spasticity, and passive range of motion (ROM) measurements.
Results: The findings indicate a reduction in spasticity in the hemiplegic arm and an improvement in functionality of the shoulder and elbow joints, as measured by various assessment tools. Key results are summarized in Table 1.
Discussion and conclusion: This case study highlights the potential benefits of combining FES and NMES in the rehabilitation of a hemiplegic arm. However, further research with a larger sample size is necessary to generalize these findings.

Table 1. Results before, during and after the intervention.

	PRE-INTERVENTION	DURING INTERVENTION	POST-INTERVENTION
ROM - Shoulder abduction	90º	90º	110º
ROM - Shoulder flexion	90º	90º	100º
MAS - Elbow flexors	2	1	1
MAS - Wrist flexors	2	1+	1
MAS - Fingers flexors	2	1	1
RMA	13	13	17

ROM: Passive range of motion. MAS: Modified Ashworth Scale. RMA: Rivermead Motor Assessment.

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FES-ASSISTED CYCLING FOR CARDIOVASCULAR AND MOTOR REHABILITATION IN SPINAL CORD INJURY: A CASE STUDY

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Introduction: Cycling training is a well-established intervention in cardiovascular rehabilitation [1] and plays a crucial role in patients with lower limb paralysis. In both cases, sustained pedaling is essential for achieving rehabilitation goals. Functional electrical stimulation (FES) applied to the quadriceps has shown promise in enhancing cycling performance and promoting continuous activity [2].

Case presentation: This case report describes a woman who, after an aortic rupture in 2009, suffered a stroke and a spinal cord injury. She exhibited partial left-sided paralysis from T12, with severe weakness in the hip and knee musculature, complete ankle inactivity, and total anesthesia in both lower limbs, preventing independent cycling. Her condition fluctuated due to blood pressure instability, low oxygen saturation, and inadequate cardiovascular response, leading to early and severe fatigue. This report explores whether FES-cycling can enhance pedaling performance, improving cardiovascular function and lower limb strength.

Methods: Fifteen years post-injury, the patient underwent a five-week rehabilitation program at Fesia Clinic (Donostia-San Sebastián, Spain), consisting of two 20-minute sessions per week. She used a cycle ergometer with minimal resistance, assisted by the Fesia Bike (Fesia Technology, Donostia-San Sebastián, Spain) for quadriceps stimulation during knee extension. Physiological parameters—blood pressure (BP), heart rate (HR), oxygen saturation (SpO2), and perceived fatigue (Borg scale)—were recorded at the start and end of each session. Additionally, SpO2, HR, and Borg scale values were monitored every minute during activity. Baseline performance was assessed by comparing cycling with and without FES assistance.

Results: Improvements were observed across all parameters. BP stabilized, SpO2 increased at session start and end, and HR fluctuations during exercise decreased, with faster recovery to baseline. Perceived fatigue, measured by the Borg scale, also declined. Key results are summarized in Table 1.

Table 1. Results before, during and after the intervention.

First Evaluation		Mid Evaluation		Final Evaluation	
Pre-Session	Post-Session	Pre-Session	Post-Session	Pre-Session	Post-Session
HR: 63 BP: 131/65 $SatO_2$: 95 Borg: 1	HR: 75 BP: 155/75 $SatO_2$: 95 Borg: 4 Time: 6 min	HR: 59 BP: 149/53 $SatO_2$: 98 Borg: 0	HR: 62 BP: 130/56 $SatO_2$: 99 Borg: 1 Time: 20 min	HR: 66 BP: 147/65 $SatO_2$: 99 Borg: 0	HR: 68 BP: 130/60 $SatO_2$: 99 Borg: 0 Time: 20 min

Discussion and conclusion: This case highlights the functional and physiological benefits of FES-cycling in a patient previously unable to sustain pedaling. The intervention improved cardiovascular and respiratory health and enhanced functional capacity, allowing her to perform daily tasks with less effort.

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EFFECT OF GAIT-SYNCHRONIZED FUNCTIONAL ELECTRICAL STIMULATION DURING EXOSKELETON-ASSISTED AMBULATION ON CARDIORESPIRATORY DEMANDS IN INDIVIDUALS WITH CHRONIC INCOMPLETE SPINAL CORD INJURY

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Introduction: Regaining gait, balance and mobility are important priorities for individuals with incomplete spinal cord injury (iSCI). Overground exoskeleton therapy has beneficial effects on gait function [1]. However, given the difficulty in recruiting muscle fibers below the level of injury after iSCI, there is potential for enhanced recruitment with functional electrical stimulation (FES). Thus, the combination of robotic therapy with gait-synchronized FES could result in increased muscle activation leading to greater cardiorespiratory demand compared to overground robotic therapy alone.
Methods: For this single measurement session employing a randomized crossover design (Fig. 1), 11 participants with chronic (>1 year) iSCI (American Spinal Injury Association Impairment Scale (AIS): B-D) and partial walking ability were recruited. Following a 5-minute resting measurement of cardiorespiratory parameters in a seated position, participants completed a familiarization 6-minute walk test (6mWT) utilizing the EksoNR powered exoskeleton (Ekso Bionics, Richmond, CA, USA) in conjunction with gait-synchronized FES (RehaMove2, Hasomed, Magdeburg, Germany), with concurrent spiroergometry monitoring (K5 wearable metabolic system, COSMED, Rome, Italy). Subsequently, participants were randomly assigned to either perform the 6mWT using the EksoNR with FES first, followed by EksoNR without FES, or vice versa (Fig. 1). A 15-minute rest period was implemented between tests to ensure recovery of cardiorespiratory parameters to baseline levels. FES was applied bilaterally to quadriceps, hamstring, gluteal, and triceps surae muscles (i.e., a total of 8 muscles) using self-adhesive electrodes. The stimulation parameters were set to a frequency of 35 Hz, a pulse width of 300 µs, and a ramp time of 1, with individually adjusted amplitudes depending on sensibility. The primary objective was to assess the within-subject difference in oxygen consumption per kilogram of body weight (VO_2/kg) during walking with the EksoNR exoskeleton with and without FES. Secondary outcomes were heart rate, respiratory minute volume (VE), and walking distance during the 6mWT. Cardiorespiratory parameters from the final 2 minutes of the 6mWT were compared using mixed linear models.
Results: Eleven participants (2 female/9 male, 49.1±15.3 years of age) with iSCI (neurological level of injury: C4-L2, AIS B-D) consented to participate. Independent of the order of conditions, VO_2/kg was 6% higher during EksoNR with FES compared to EksoNR without FES (15.1±4.1 vs. 14.2±3.6 $mL*min^{-1}*kg^{-1}$, p=0.018). Similarly, heart rate (98.5±16.0 vs. 95.8±15.9 beats per minute, p=0.030) and VE (34.7±9.2 vs. 32.0±7.8 $L*min^{-1}$, p=0.023) were also elevated with gait-synchronized FES. Notably, similar distances were covered for both conditions during the 6mWT (130±43 vs. 127±40 m, p=0.32). The individual difference in VO_2/kg between EksoNR with FES and without FES was not explained by the stimulation amplitude (R=0.36, p=0.27).
Discussion and conclusion: The combination of training with a powered exoskeleton and gait-synchronized FES led to a consistent increase of cardiorespiratory parameters in 10/11 participants. FES presents a promising method for enhancing training intensity during robotic-assisted gait training. This approach potentially acts over the activation of additional muscle fibers and the stimulation of the autonomic nervous system. Ongoing investigations aim to determine whether extended training over 8 weeks (3x/week) with this combined modality yields improved clinical outcomes.

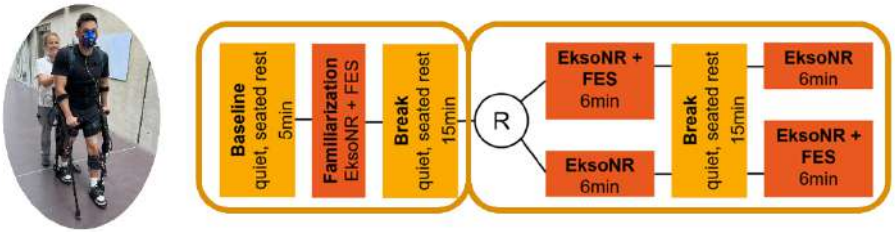


Figure **1**: Subject using the EksoNR exoskeleton with gait-synchronized FES during spiroergometry testing, alongside an overview of the study process featuring a randomized cross-over design after a resting and a familiarization measurement.

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ENHANCING NEUROMUSCULAR RECOVERY AND GAIT FUNCTION THROUGH FES AND EXERCISE AFTER TIBIALIS POSTERIOR TENDON TRANSFER FOR FOOT DROP

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Introduction: Peroneal nerve mononeuropathy is the most common neuropathy of the lower extremity and a leading cause of foot drop. Anterior transfer of the tibialis posterior tendon is an effective surgical intervention to improve functional activities and gait in cases of foot drop caused by peroneal nerve palsy [1]. Additionally, electrical stimulation (ES), including direct muscle stimulation (DMS), electrical muscle stimulation (EMS), and functional electrical stimulation (FES), is widely recognized as a valuable tool for rehabilitating foot dorsiflexor function in individuals with peroneal nerve neuropathy and foot drop [2]. By delivering targeted electrical impulses, FES activates specific muscles, improving dorsiflexion during the gait cycle, enhancing gait quality, and promoting functional independence [3].
Objective: This case report describes the rehabilitation approach combining DMS, EMS, FES, and therapeutic exercise to improve ankle dorsiflexion strength, activation, range of motion (ROM), and gait function in a patient who underwent tibialis posterior tendon transfer surgery for foot drop correction.
Methods: The participant, a 49-year-old female with a 10-year history of traumatic peroneal nerve neuropathy, underwent tibialis posterior tendon transfer surgery four months prior to the intervention. She followed an 18-week rehabilitation protocol consisting of ES combined with therapeutic exercises targeting dorsiflexion strength and ankle proprioception, performed twice a week. Each session included 20 minutes of DMS (manufacturer-predetermined frequency: 1/30 Hz – 10 Hz, pulse width: 180 ms, intensity: 10–15 mA) applied to the tibialis anterior, EMS (frequency: 75 Hz, pulse width: 250 µs, intensity: 20–35 mA) applied to the tibialis posterior, and 40 minutes of therapeutic exercise combined with FES (frequency: 15 Hz, pulse width: 300 µs, intensity: 25–35 mA) applied to the tibialis anterior using the Fesia Walk (Fesia Technology, Donostia-San Sebastián, Spain). Neuromuscular assessments included ankle dorsiflexor strength measured with the Modified Medical Research Council Scale (mMRC) and active ROM evaluations. Surface electromyography (EMG) with the mDurance (mDurance, Granada, Spain) device was used to assess tibialis anterior and peroneal muscle activation.
Results: The intervention led to significant improvements in dorsiflexor muscle strength (mMRC score increased from 1 to 3) and active ROM (from -53º to 2º of active dorsiflexion). EMG measurements showed increased activation of the tibialis anterior and peroneal muscles, reducing foot drop severity. These gains translated into improved gait functionality and greater independence in daily activities.
Discussion and conclusion: This case report highlights the potential benefits of combining DMS, EMS, and FES with therapeutic exercise in the rehabilitation of patients undergoing tibialis posterior tendon transfer for foot drop. This multimodal approach enhanced dorsiflexion capacity, gait mechanics, and overall functional independence, suggesting its value as an adjunct in post-surgical rehabilitation.

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FULLY AUTOMATED COMPUTER-CONTROLLED ELECTRICAL PERCEPTUAL THRESHOLD SYSTEM FOR SENSORY ASSESSMENT

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Introduction: This study introduces a computer-controlled electrical perceptual threshold (CCEPT) testing device, a fully automated sensory assessment system for quantifying sensory perception in individuals with spinal cord injury (SCI). Inspired by the manual electrical perceptual threshold (EPT) developed in 2006 [1], the CCEPT offers uniform stimulus delivery and accurate, unbiased response recording.

Methods: Perceptual threshold to 3 Hz cutaneous electrical stimulation was measured in 12 non-disabled individuals (8 males and 4 females, ages 19 to 67 years and a mean age of 31.3±16.4 years) using a fully automated CCEPT device (Fig. 1). The CCEPT system employed cutaneous electrical stimulation (0.5 ms monophasic square pulse width, at 3 Hz) in randomly bilateral stimulation of 52 dermatomes from C2-S2. The perceptual thresholds from the fully automated CCEPT measurements were compared to the healthy perception thresholds derived from manual EPT tests [1]. Side-to-side reliability (left vs. right) was evaluated using Spearman correlation (r) and intraclass correlation coefficient (ICC(2,1)). Also, Wilcoxon signed-rank tests assessed systematic differences between sides. For graphical visualisation of the left vs. right comparison, Bland-Altman plots visualised agreement between sides, and scatter plots were examined for correlation trends. In addition, within-session consistency was evaluated using the Friedman test. Test-retest reliability over two sessions (two weeks apart) was also examined using ICC (2,1). Bland-Altman and scatter plots were used to visualise agreement between sessions.

Results: The CCEPT perceptual threshold plot closely followed the healthy perception threshold reported [1]. Spearman correlation analyses indicated strong left-right associations (Session 1: $r = 0.87$, $p < 0.001$; Session 2: $r = 0.86$, $p < 0.001$). ICC(2,1) values were 0.97 (95% CI: [0.91, 0.99], $p < 0.001$) in Session 1 and 0.89 (95% CI: [0.67, 0.97], $p < 0.001$) in Session 2, indicating excellent reliability between left and right sides. Bland-Alman plots indicated minimal bias between sides, with a mean difference of 0.034 mA (Session 1) and 0.087 mA (Session 2), reflecting high agreement. Wilcoxon tests found no significant differences between the left and right sides (Session 1: $p = 0.48$; Session 2: $p = 0.21$), supporting symmetrical sensory perception. Within-session reliability analysis (Friedman test) showed significant differences across trials in Session 1 ($p < 0.001$) but not in Session 2 ($p = 0.12$). However, Cohen's d-effect sizes were negligible in both sessions (0.024-0.094), indicating minimal practical differences between trials. Meanwhile, the test-retest reliability (ICC(2,1) = 0.86, 95% CI [0.60, 0.96], $p < 0.001$) demonstrated excellent consistency across dermatomes, with scatter and Bland-Altman plots confirming a high agreement between sessions.

Discussion and conclusion: The results of this study suggest that the CCEPT measurements are reliable and consistent with symmetry in sensory perception and patterns, matching the healthy perception threshold from manual EPT tests [1]. Findings highlight CCEPT is a promising, innovative method for assessing multiple dermatomes with a standardized, uniform, and fully automated protocol. Additional investigations are needed to evaluate the psychometric properties of the CCEPT further as an outcome measure for clinical and research use in the SCI population.



Figure **1**: CCEPT Device Setup

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The Frequency-Dependent Effects of Tibial Nerve Stimulation on Bladder Function

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Introduction: Disorders of the lower-urinary tract manifest as a failure to initiate (urinary retention) or prevent (urinary incontinence) voiding [1]. The treatments available for urinary retention are limited. Typical interventions posses significant side effects or require invasive medical procedures [2]. However, by modulating the urination control circuit, it is possible to alter the activity of the bladder [3] . Non-invasive treatment options targeting the tibial nerve (transcutaneous tibial nerve stimulation, TTNS) are presently used by the NHS, but only for incontinence. To date, some research has examined using TTNS for the treatment of urinary retention [4], with mixed results. To this end, our research aimed to further explore the feasibility of TTNS as a treatment for urinary retention.

Methods: Computational results were generated using an adapted model of the control circuit [5] and bladder (in prep) modified to include tibial nerve projections. The firing rate of the tibial nerve could be arbitrarily set. To analyse the effects of stimulation frequency, simulations were run under 3 states (0, 1, 20 Hz). Additionally, a pilot study was run in a healthy population (N=40) to validate the effects of TTNS on bladder sensation. Participants were asked to consume 750ml of water and administered stimulation (monophasic, 200μs pulse-width, at motor threshold) via electrodes placed 1cm posterior to-, and 10cm cephalad to the medial malleolus. Stimulation was 1Hz (Group A, 0.02% duty cycle), 20Hz (Group C, 0.4% duty cycle) or 0Hz (Group B). The researchers recorded the time elapsed before participants experienced the first sensation that they needed to urinate.

Results: The computational work suggests that there is a frequency dependent effect of TTNS. Low-frequency TTNS induced earlier voiding, lowering bladder capacity while high-frequency TTNS prevented voiding at all within the simulated timespan (see Figure. 1 left). The results of the pilot study corroborate these findings. Group C (20Hz) took significantly longer, and group A (1Hz) significantly less time to experience the urge to urinate compared to the control (Group B) (see Figure. 1, right).

Discussion and conclusion: The results of this study for the first time display the existence of a frequency dependent effect of TTNS in human participants. They also provide a computational framework for further analysis of the intervention which is not presently available. The results have considerable clinical implications on the treatment of urinary retention.

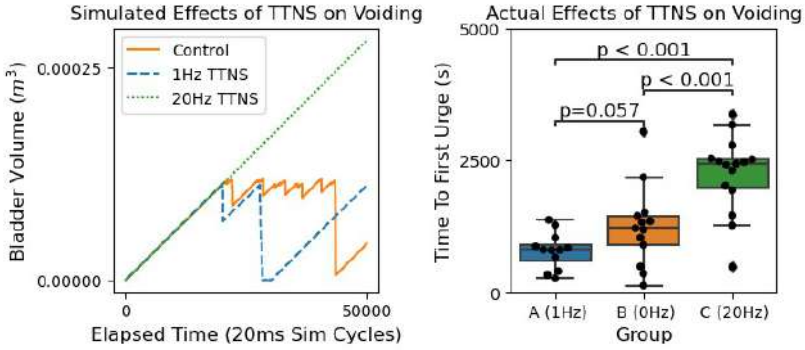


Figure 1. Simulated (left) and real-world effects (right) of TTNS on bladder function.

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STOCHASTIC RESONANCE ELECTRICAL STIMULATION ENHANCES SOMATOSENSORY PERCEPTION IN CEREBRAL PALSY – Pilot Study

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Introduction: People with Cerebral Palsy (CP) have a high risk of falls, leading to serious injuries. Recent research in CP suggests sensory deficits contribute to balance impairments [1]. Falls occur due to deficits in the motor system, i.e., failures in generating appropriate motor responses, and or deficits in the sensory system, i.e., somatosensory impairments preventing accurate feedback of position and movements of the body in space. Multiple interventions focus on improving motor responses in CP, however, sensory modulation approaches that may enhance proprioception are currently under-explored. Stochastic resonance (SR) stimulation can improve the sensitivity of the sensory system to detect a weak signal and has shown promising results in populations with sensory deficits, such as diabetic neuropathy and stroke. Our previous work found proprioceptive SR stimulation can significantly decrease postural sway during standing [2] and improve balance responses during walking [3] in people with CP. Our observations indicated SR stimulation played a role in improving sensorimotor function; however, we did not directly test the effect of SR stimulation on somatosensory perception. The present work studies the effect of SR stimulation on somatosensory perception in people with CP.

Methods: The study team developed a protocol to assess the effect of SR on somatosensation perception tests. Ten individuals with CP (GMFCS level I (3), II (5), and III (2)) performed four different somatosensation perception tests: vibration sense, joint position sense, two-point discrimination, and light touch pressure, with and without SR stimulation. All testing was performed on the more affected side while participants lay supine with closed eyes. SR stimulation was applied to the muscles and ligaments of the ankle and hip joints.[3]

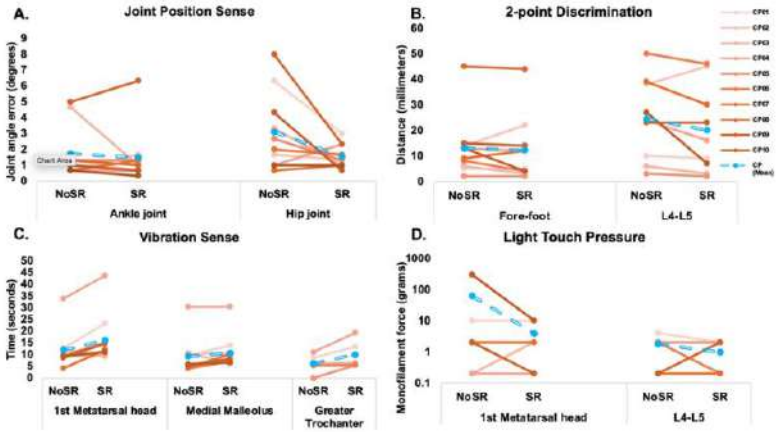


Figure 1: Effect of SR on somatosensation perception tests for individuals with CP. Individual and mean scores for (A) Joint position sense, (B) 2-point discrimination, (C) Vibration sense, and (D) Light touch pressure from 3 trials each, with and without SR. Smaller values imply better somatosensation for all except vibration sense, where longer durations indicate improvement.

Results: SR stimulation improved joint position sense at both the ankle and hip joints (Fig. 1A). Two-point discrimination improved slightly at the forefoot, while greater improvements were observed at the L4-L5 dermatome (2 inches above the lateral condyle of the femur on the lateral side of the thigh) (Fig. 1B). Vibration sense improved at the first metatarsal head and the greater trochanter; however, slight increases were present at the medial malleolus (Fig. 1C). SR stimulation improved light touch pressure sensation at the 1st Metatarsal head and L4-L5 dermatome (Fig. 1D). CP5 could not detect vibration at the greater trochanter, which interestingly could be detected with the SR application. Five participants could not detect vibration at the greater trochanter, one could not detect 2-point discrimination, and two could not feel light touch at the L4-L5 dermatome.

Discussion and conclusion: SR stimulation improves somatosensory perception in CP, which may be more prevalent when tested on a larger group. These findings demonstrate that SR can differentially enhance somatosensory modalities, which may be critical in advancing combined sensory-motor rehabilitation techniques.

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FUNCTIONAL ELECTRICAL STIMULATION CYCLING: A CLINICAL PRACTICE GUIDELINE FOR SPINAL CORD INJURY REHABILITATION

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Introduction: Functional electrical stimulation (FES) cycling has evolved from rehabilitation strategy to competitive sport to leisure activity for individuals with spinal cord injury (SCI) (Fig.1). For people living with SCI, this intervention has resulted in improvements in muscle health, lower-body power output, and aerobic fitness[1]. These improvements may help to reduce complications associated with SCI, as well as cardiovascular and cerebrovascular conditions. Despite its growing prevalence worldwide, there is no consensus on specific guidelines for FES cycling. Clinical practice guidelines are needed to synthesize evidence-based research to assist with clinical implementation, patient expectations, and physical recovery from SCI. Therefore, we aimed to produce an international clinical practice guideline for FES cycling for SCI rehabilitation informed by current research evidence and expert opinion.

Methods: A guideline development group (GDG) of FES cycling experts was formed to oversee the creation of the clinical practice guideline. Following an update to the systematic review[1], new research articles were evaluated using the GRADE approach to rate evidence quality. Then, a smaller working group (HJ-R, KM, AG, IB-P, CH) drafted a long list of consensus statements from the included articles. This long list was refined by the GDG into a short list. To establish consensus, we used a 3-step modified Delphi method[2]. Experts representing people with SCI, healthcare professionals (HCPs) or researchers were invited to evaluate the statements. In round 1, the validation round, panel members assessed each statement for clarity, marked "yes" or "no", and provided comments. The GDG reviewed these comments and revised the statements for clarity. In rounds 2 and 3, participants rated each statement using a 9-point Likert scale and provided comments[3]. The statement was forwarded to round 3 if $\leq$15% rated the statement between 1-3 and $\geq$50% rated the statement between 7-9 within two subgroups. All statements were distributed to the expert panel via REDCap survey software. The AGREE-II instrument was used to guide clinical practice guideline development and reporting[4].

Preliminary Results: Consensus statements were organized into eight categories (Tab.1). In round 1, Thirty-four statements within six categories were presented for validation by 38 participants. There were 2 dropouts between rounds 1 and 2. Thirty-six individuals (8 people with SCI,18 HCPs, 10 researchers) evaluated 33 statements in round 2. Thirty-three statements met consensus criteria while no statements were identified for round 3 according to subgroup analyses.

Discussion and conclusion: The clinical practical guideline will serve as a resource to guide HCPs as they integrate FES cycling into clinical practice for SCI rehabilitation. It will be composed of finalized categories and statements supported by corresponding research evidence. Subsequent steps should focus on shaping regional implementation strategies.



Figure **1**: Functional electrical stimulation cycle user

Table 1: Final consensus statement categories

Statement category
1. Metabolism and body composition
2. Cardiovascular fitness and vascular health
3. Musculoskeletal structure and function and bone health
4. Functional and neurological changes and cycling performance
5. Well-being and psychosocial
6. FES cycling parameters and dosages
7. Progressions and recommendations
8. Other

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OPTIMAL FES ELECTRODE PLACEMENT FOR FES SEMI-RECUMBENT CYCLING: A SIMULATION STUDY

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Introduction: Clinically available cycling ergometers use standardised FES electrode placements, as seen in numerous studies (20 studies 1988-2021 from PubMed Search used the same configurations as [1]). As many clinically available stimulation systems are on the market, channel numbers vary from three to six per leg, giving clinicians many choices to apply FES electrodes. This study used neuromusculoskeletal modelling to simulate different FES electrode placement configurations (CFGs) to determine which CFG would best reproduce joint moments during voluntary cycling.
Methods: Eleven uninjured participants performed cycling at 15W at 40 RPM where pedal reaction forces, and motion were recorded simultaneously. A validated biomechanical modelling pipeline in OpenSim/CEINMS calculated hip and knee moments of different FES electrode CFGs using grouped muscle static optimisation that solved, at each timeframe, an optimisation problem that minimised muscle activation (Figure 1, left) while tracking experimental joint moments. A total of eleven CFGs were analysed to determine performance by comparing the estimated joint moments from the laboratory to the simulated joint moments of each CFG. CFGs were grouped based on the number of used channels, and comparisons were performed within each group. Twelve cycles per person were extracted and resampled to 360 points. Bonferroni corrected paired t-tests were used to determine significant differences between CFGs ($P<0.005$).
Results: Joint moment tracking (Fig 1, right) in the three-channel group showed CFG 1 was significantly better than CFG 2 at the knee ($P=0.004$). In the four-channel group, CFG 5 was significantly better than CFG 3 ($P=0.004$) and CFG 4 ($P=0.016$) for the hip, and CFG 4 was significantly better than CFG 3 ($P=0.004$), CFG 5 ($P=0.003$), and CFG 6 ($P=0.003$) at the knee. In the five-channel group, CFG 9 was significantly better CFG 8 ($P=0.01$) and CFG 7 ($P=0.008$) at the hip, however, CFG 7 was significantly better CFG 8 ($P=0.004$) and CFG 9 ($P=0.010$) at the knee. In the six-channel group, CFG 10 performed better than CFG 11 but not significantly, however CFG 10 outperformed 11($P=0.003$) at the knee.
Discussion and conclusion: This study offers guidance on selecting muscle groups for FES cycling based on available channels. With three electrodes, gluteal stimulation may not be needed, which may simplify clinical workflow. Targeting the vasti and rectus femoris improved hip joint moment tracking but affected knee moment tracking. Whilst we generated optimal stimulation patterns, electrode placement in clinical settings may be limited by available stimulation patterns.

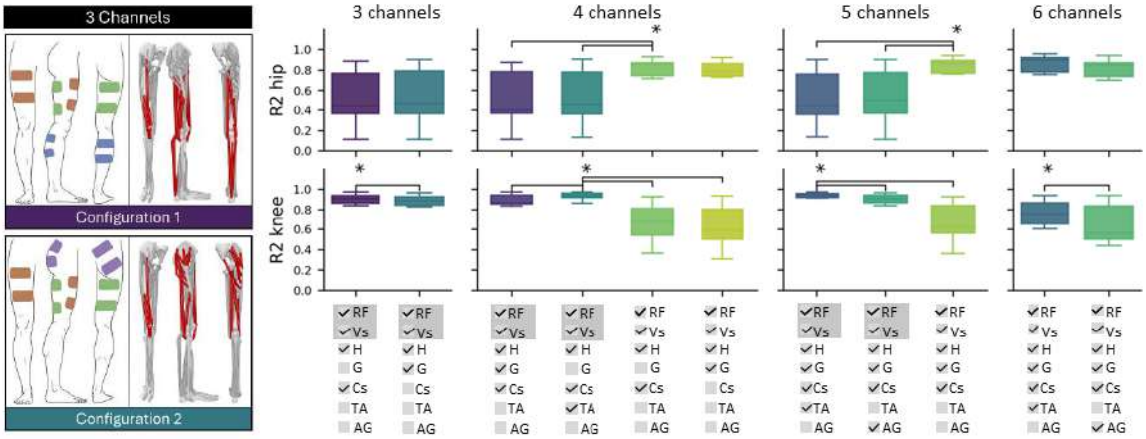


Figure 1: Left: active muscles (red) are stimulated and passive muscles (grey) track joint moments. Right: R2 calculated between experimental and estimated hip and knee moments for eleven stimulation configurations. Configurations are split in groups of FES channel numbers: 3, 4, 5, and 6. Star and bars above the plot denote significant differences between configurations where the best configuration in each group was compared to the runners up.

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THE EFFECT OF FES MODULATION ON HIP MECHANICAL LOADS: A SIMULATION STUDY

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Introduction: While offering cardiometabolic benefits, effectiveness of FES cycling in increasing bone mineral density following spinal cord injury remains unclear [1]. Inconsistent results may stem from using default manufaturer stimulation patterns (e.g., start/stop angles, amplitude), which could lead to suboptimal (i.e., too little/high) mechanical loads unable to promote favourable bone adaptions [2]. This study aimed to simulate hip mechanical loads during semi-recumbent cycling using generic and personalised FES, comparing these loads with those from voluntary semi-recumbent cycling.
Methods: Eleven uninjured participants performed voluntary cycling at 15W at 40rpm where electromyograms (EMG), pedal reaction forces, and motion were recorded. A validated biomechanical modelling pipeline in OpenSim/CEINMS using an EMG-assisted neuromusculoskeletal model [3] estimated magnitude and direction of the 3D hip mechanical load vector during voluntary cycling. Two stimulation patterns were also simulated: (i) personalised stimulation, and (ii) default stimulation (ERGYS [4]). The personalised stimulation was calculated by solving an optimisation problem that minimised muscle activations while tracking experimental joint moments. Twelve cycles resampled to 360 points were extracted per person. Paired SPM1D t-tests between voluntary and simulated stimulation were performed post-hoc.
Results: The personalized FES and generic stimulation had hip contact force had magnitudes equal to or less than those in voluntary cycling (Fig. 1, right). Both personalized and generic FES resulted in hip contact force directions that were closer to the acetabular rim compared to voluntary cycling.
Discussion and conclusion: We compared the effects of different FES stimulation on hip loading to voluntary cycling. Generic FES produced significantly lower hip contact forces than voluntary cycling. For 40% of the total crank cycle, the direction of the generic contact forces was either towards or outside the acetabular rim, potentially causing harmful bending moments on the femoral neck. In contrast, personalized stimulation resulted in hip loads closer to loads in voluntary cycling, suggesting a safer approach for promoting favorable bone adaptations. Future research should assess the impact of these loads on bone health using finite element analysis tailored to individual bone geometry.

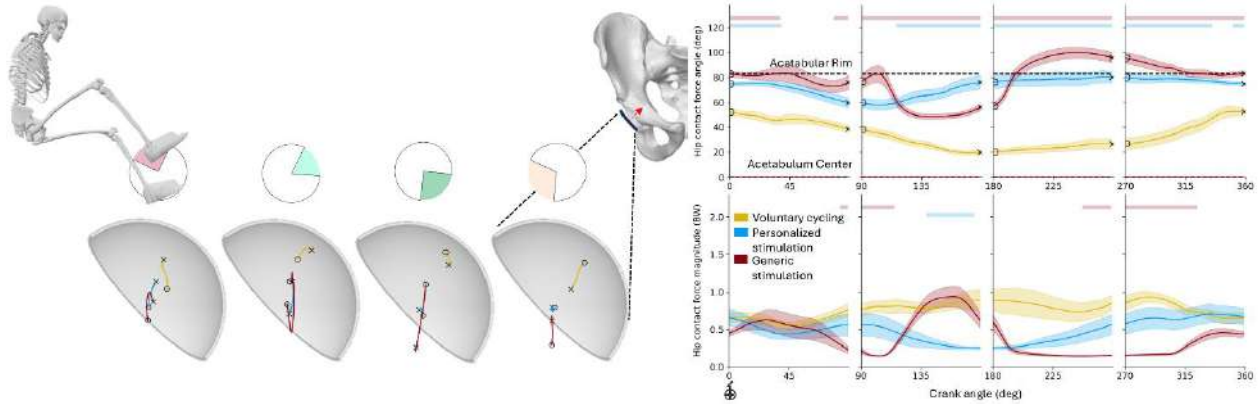


Figure 1: Cycling regions represent hip flexion and extension phases. Left: hip loading traces in the acetabulum. Right: hip loading direction and magnitudes. Zero degrees on the x-axis denotes top dead centre. Solid line: mean; shaded regions: standard error of the mean. Coloured bars: significant differences between simulations and voluntary cycling.

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FEASIBILITY AND SAFETY OF AUTOMATED MULTI-CHANNEL FES-ASSISTED GAIT TRAINING IN INCOMPLETE SPINAL CORD INJURY

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Introduction: Studies that investigated the effects of locomotor training with functional electrical stimulation (FES) have shown improved function of the lower limbs in those with incomplete SCI (iSCI). However, in most studies the stimulation was activated manually and only one or two lower-limb muscles were stimulated during gait. Automatically activating more lower-limb muscles might more effectively enhance gait patterns, but has not been studied yet. The primary aim of this study, therefore, was to investigate the feasibility and safety of automated multi-channel FES-assisted gait training for people with iSCI. We also aimed to assess possible improvements in gait function.
Methods: Five individuals with chronic iSCI (≥12 months post-injury, ASIA C/D) participated in a 10-week FES-assisted gait training (2*/wk, 30 min) on a motorized treadmill. FES was applied to the quadriceps, gluteal, hamstring, tibialis anterior and gastrocnemius muscles using an electrical stimulation suit with built-in surface electrodes and motion capture sensors (Teslasuit, VR Electronics Ltd, London, UK). Stimulation intensity was set for each muscle during the first training session, but could be adjusted if necessary during subsequent sessions. A stimulation profile (stimulation as a function of time) was triggered after initial contact detected by the embedded motion capture sensors. Feasibility and safety were evaluated via self-administered questionnaires, missed training sessions, and number of (serious) adverse events. Gait function (without FES) was assessed using a 10-meter overground walk test at pre- and post-intervention, and at 10-week follow-up. Spatiotemporal parameters were measured during the 10-meter walk test.
Results: All participants completed the intervention, with an average of 1.5 missed sessions (91% completion rate). Most participants showed an increase in walked distance during the intervention period (Fig. 1). Participants reported that the stimulation aided them during walking, noting positive effects such as increased ability to lift their legs, reduced foot dragging, and enhanced walking speed. All participants reported the desire to continue this gait training. Participants experienced temporary skin redness after each session. No other (serious) adverse events were reported. Although four participants showed an increased overground walking speed post-intervention (Fig. 2), improvements in walking speed, step length, step width, and cadence were not statistically significant across pre-, post-, and follow-up measurements.
Discussion and conclusion: The automated multi-channel FES-assisted gait training was feasible, safe and well-appreciated by all participants and led in 4 of the 5 participants to gait improvement. Significant improvements in walking speed, step length, step width, and cadence at pre-, post- and follow-up were not observed for the whole group, which could be due to considerable individual variability in response to the FES-assisted gait training and limited sample size. Further randomized controlled trials with larger cohorts are needed.

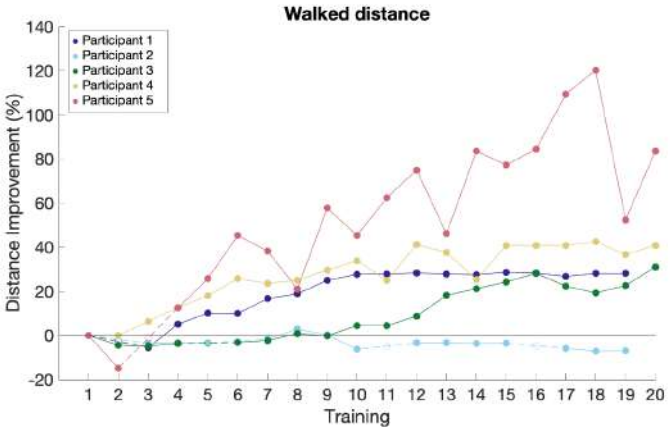


Figure 1. Changes (%) in walked distance compared to the first training session.

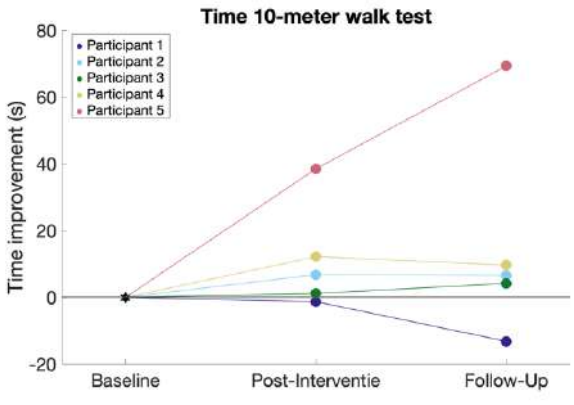


Figure 2. The time improvement (s) on the 10-meter walk te

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An Intention-Driven Hybrid Electrical Stimulation Glove for Post-Stroke Hand Rehabilitation

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Introduction: Stroke is one of the leading causes of long-term disability, often resulting in upper limb paralysis that severely affects hand motor function and limits the ability to perform activities of daily living (ADLs). Functional electrical stimulation (FES) therapy has been widely used as a rehabilitation method to restore motor function by applying electrical stimulation to paralyzed muscles. However, most conventional FES devices require additional movements unrelated to the intended movement to trigger electrical stimulation, leading to asynchronous activation that does not align with the user's intent. Considering that immediate feedback associated with the user's intention is crucial in neuroplasticity [1], asynchronized electrical stimulation can hinder rehabilitation outcomes and limit the patient's active involvement. To address this issue, this study presents a novel electrical stimulation glove for hand rehabilitation, driven by the recognized user's intent.

Methods: The glove, illustrated in Fig. 1(a) and (b), integrates a hybrid actuation mechanism combining a silicone strap and electrical stimulation. The silicone strap, utilizing its elasticity, generates sufficient force to extend a stroke patient's clenched hand, enabling passive finger extension without requiring any active force [2]. Electrodes for finger flexion and extension are placed on the forearm, targeting the flexor digitorum and extensor digitorum muscles, respectively. Additionally, a capacitance-based strain sensor embedded in the silicone strap measures strain on the index finger and thumb [3]. Machine learning algorithms analyze the strain data to identify the user's intent for finger flexion and extension. The strain sensor on the index finger detects the intention to flex the finger, while the sensor on the thumb identifies the intention to extend it, for activating electrical stimulation for the corresponding muscles.

Results: Task-oriented rehabilitation training with the glove demonstrated its effectiveness in assisting object grasping and releasing by recognizing the user's intent. When the index finger flexes, the system detects the intention and activates electrical stimulation to the flexor digitorum, allowing the user to grasp an object (Fig. 1(c)). Similarly, when the thumb extends, the system recognizes the intention and applies electrical stimulation to the extensor digitorum, enabling the user to release the object (Fig. 1(d)).

Discussion and conclusion: This study developed a novel electrical stimulation glove for hand rehabilitation that addresses the limitation of conventional FES devices. The hybrid actuation mechanism enables finger flexion and extension, while the control strategy based on the intention ensures synchronized movements with the user's intention. Task-oriented rehabilitation confirmed the glove's functionality in assisting object grasping and releasing effectively. Future studies will focus on validating long-term efficacy through clinical trials.

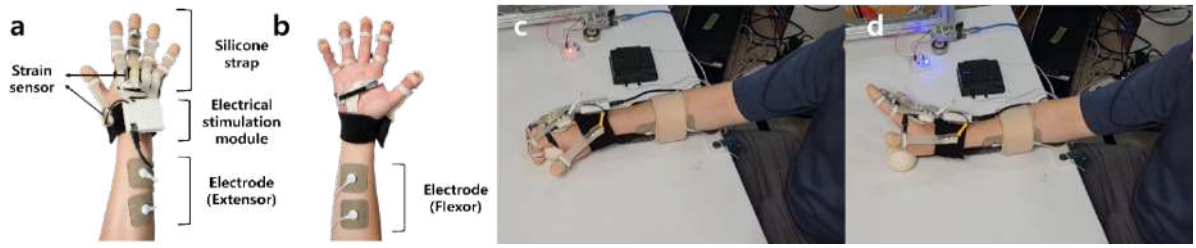


Figure **1**: Overview of the proposed electrical stimulation glove for hand rehabilitation. (a) Dorsal view of the glove. (b) Palmar view of the glove. (c) Object grasping triggered by the intention of finger flexion. (d) Object releasing triggered by the intention of finger extension. The red and blue LED lights indicate the intentions of finger flexion and extension, respectively.

Acknowledgments: This study was supported by the Translational Research Program for Rehabilitation Robots(#NRCTR-EX24007), National Rehabilitation Center, Ministry of Health and Welfare, Korea.

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Case Study from the Cybathlon 2024: Rehabilitation Effects of Functional Electrical Stimulation Cycling

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Introduction: Imagine a world where individuals who have lost the ability to walk can once again experience the thrill of movement and regain their sense of freedom. Functional electrical stimulation (FES) is making this vision a reality by enabling paraplegic individuals to restore muscle function through controlled electrical stimulation. By applying electrical impulses to targeted muscles, FES triggers contractions that promote active rehabilitation [1]. The Cybathlon FES-Bike discipline is one of the most exciting demonstrations of FES technology, where individuals with spinal cord injury (SCI) use FES to cycle over challenging distances (1960 meters in 8 minutes). This competition not only pushes the limits of muscle performance but also shows how technology can empower SCI athletes to overcome barriers once thought insurmountable. Our journey shows how FES can transform rehabilitation, restoring physical function and enabling participation in competitive sports, proving that physical limitations can be overcome with proper technology and training.

Methods: Our pilot (born 1972, male, ASIA A) underwent an intensive 15-month training regimen involving consistent FES cycling exercises (Fig. 1). Each session included one hour of leg stretching, followed by FES cycling sessions lasting over two hours with intermittent rest. Training frequency (30 to 50 Hz) and intensity (50 to 130 mA, 1 to 1.5 ms pulse width, and symmetrical biphasic pulse) were gradually increased, reaching high-intensity sessions six days per week during the final stages. Stimulation parameters were adjusted to optimize muscle engagement, with progress tracked for growth, power, and endurance. Body composition changes were measured using a bioelectrical impedance analysis device (BWA 2.0, InBody), tracking metrics such as body fat mass and soft lean mass of the lower limbs. Thigh and calf circumferences, muscle mass, and body weight were recorded throughout the program. This study received approval from the Yonsei University Institutional Review Board (IRB No. 7001988-202406-HR-1604-05).

Results: Our pilot showed significant improvements in muscle strength, body composition, and overall fitness over the 15-month training period. Thigh circumference increased significantly, indicating substantial muscle hypertrophy (Tab. 1). Calf circumference also grew, and lean muscle mass of the lower limbs increased from 18.41 kg to 18.73 kg. Body fat mass decreased, emphasizing improved body composition and fitness. These gains contributed to a successful performance in the Cybathlon FES-Bike competition, showcasing the effectiveness of our training program.

Discussion and conclusion: Our FES training program demonstrates significant rehabilitation potential for individuals with SCI, offering not only physical benefits but also inspiration through participation in the Cybathlon. This achievement provides hope and encouragement to other SCI patients, showcasing that remarkable progress is possible with determination and support. Looking ahead, we plan to refine and expand our training protocol to validate its effectiveness across diverse populations, highlighting how FES technology can empower individuals with SCI to achieve enhanced independence.



Figure **1**: Team BeAGain in Cybathlon 2024.

Table 1: Physical changes resulting from our training (L and R denote the left and right sides, respectively).

Date	Thigh circumference (cm)	Calf circumference (cm)	Weight (kg)	Body fat mass (kg)	Soft lean mass of lower limbs (kg)
23.07	L43.7 / R44.0	L33.5 / R33.5	N/A	N/A	N/A
24.06	L53.0 / R53.5	L35.2 / R35.5	81.9	24.3	18.4
24.09	L52.0 / R52.1	L36.9 / R37.3	79.3	21.6	18.7

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ELECTRICAL STIMULATION TO PREVENT RECURRING PRESSURE ULCERS IN INDIVIDUALS WITH A SPINAL CORD INJURY

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Introduction: Pressure ulcers (PUs) on the buttocks are among the most common secondary complications in individuals with chronic spinal cord injury (SCI). PUs can result from sitting for extended periods, disuse atrophy, increased sitting pressure and reduced circulation. Compared with usual care, activation of paralysed muscles using electrical stimulation (ES) has been shown to markedly increase paralysed muscle mass, improve circulation of skin and muscle and improve sitting pressure distribution [1]. ES might therefore be a useful method to reduce PU incidence.This study assessed the effectiveness of regular (≥ 4x/week) ES targeting the gluteal and hamstring muscles in preventing PUs and enhancing potential risk factors, such as local circulation and muscle thickness in individuals with SCI.

Methods: A multicenter randomized-controlled trial. Inclusion criteria comprised complete or incomplete SCI, intact gluteal and hamstring muscles, and ≥1 PU occurrence in the last 5 years. The intervention included home-based ES using a portable stimulator, self-adhesive electrodes, or custom lycra garment (Fig.1). Participants were instructed to apply ES for ≥60 minutes, ≥4 days per week, over a year, alongside usual care. The control group received only usual care. PU incidence (primary outcome) was assessed biweekly using standardized buttock images. Secondary outcomes, including deep femoral artery blood flow, arterial diameter, and gluteal muscle thickness, were measured with ultrasound. Data collection occurred at baseline (T0), 3, 6 (T2), and 12 months. Preliminary 6-month data are presented.

Results: PU incidence was 29% in the intervention group (N=24) and 33% in the control group (N=18) (Odds ratio: 0.824 (95%CI: 0.22–3.07)). Resting blood flow (L/min): intervention (T0: 0.15±0.1, T2: 0.20±0.11) and control (T0: 0.14±0.09, T2: 0.15± 0.07), Beta (standard error (SE)):0.05 (0.018). Arterial diameter (cm): intervention (T0: 0.38±0.12, T2: 0.41±0.1) and control (T0: 0.36±0.09, T2: 0.37±0.08), Beta (SE):0.023 (0.014). Muscle thickness for gluteus maximus (cm): intervention (T0: 1.7±0.51, T2: 1.9±0.52) and control (T0: 1.7± 0.46, T2: 1.7± 0.47), Beta (SE):0.206 (0.079).

Discussion and conclusion: The preliminary results suggest that regular use of ES targeting the gluteal and hamstring muscles may have a positive impact on preventing PUs in individuals with SCI. The intervention group showed a tendency towards lower incidence of PUs compared to the control group, indicating a potential benefit of ES in reducing PU occurrence. Additionally, the observed increases in resting blood flow and arterial diameter in the intervention group suggest that ES may enhance local circulation, which could contribute to PU prevention. The slight increase in gluteus maximus muscle thickness in the intervention group also points towards a potential for ES to mitigate disuse atrophy, further supporting its role in PU prevention. The use of ES appears to be a promising method for reducing the incidence of PUs in individuals with SCI. These findings warrant further investigation with a larger sample size and longer follow-up to confirm the effectiveness of ES in PU prevention. If confirmed, ES could be incorporated into standard care practices for individuals with SCI to reduce the risk of PUs and improve overall quality of life.



Figure 1. Lycra garment with built-in surface electrodes (Berkelbike, the Netherlands)

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Smart Electrical Stimulation and Musculoskeletal Re-Education following injury

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Anterior cruciate ligament (ACL) injuries are associated with significant neuromuscular deficits and rehabilitation is a lengthy and arduous process. Despite significant investments in intensive rehabilitation by elite sports institutions, these injuries often have lasting effects. Athletes face risks of re-ruptures, reduced performance, loss of function, and development of chronic degenerative knee diseases (Buckthorpe et al., 2024).

Due to the negative impact of ACL injuries on the internal muscle force distribution in the knee joint, which leads to altered force patterns and increased risk of further damage, modifying these forces is essential.

Previous research has demonstrated promising results in altering loading of the knee joint using FES to stimulate the biceps femoris long head muscle during stance phase to effectively restrict knee internal rotation torque in gait. (Azmi et al., 2018)

We aim to translate this technology into practical applications, which necessitates the development and validation of the Biostim. The Biostim is a wearable device, developed by Biomex Ltd, with embedded IMUs to detect gait phases using onboard prediction. The onboard prediction is based on a machine learning classifier. The device is designed to deliver targeted functional electrical stimulation (FES) at the right moments during the gait cycle. This method not only combats muscle inhibition and atrophy but also possibly provides feedback stimuli for neuromuscular re-training, supporting the patient's progressive recovery of neuromuscular coordination during the early and middle stages of rehabilitation (Labanca et al., 2022).

Furthermore, we are investigating the potential of using optical 3d body scanning technology to monitor the overall rehabilitation progression by analysing segmental volumes and tracking changes over time as well as asymmetries. Preliminary results show differences between control subjects and individuals recovering from ACL injury in terms of lower-body segmental volumes.

To validate the device, a parallel, single-blind, randomised controlled intervention trial will start early 2025. The control arm will undergo normal standard of care rehabilitation as per KNGF guidelines (van Melick et al., 2016); the intervention arm will undergo the same whilst incorporating BioStim usage during part of the rehabilitation sessions. The primary hypothesis of the investigation is that treatment with the BioStim device, by stabilising the knee and providing a stimulus driving neuromuscular re-training, will enable an enhanced and more rapid recovery for athletes in rehabilitation.

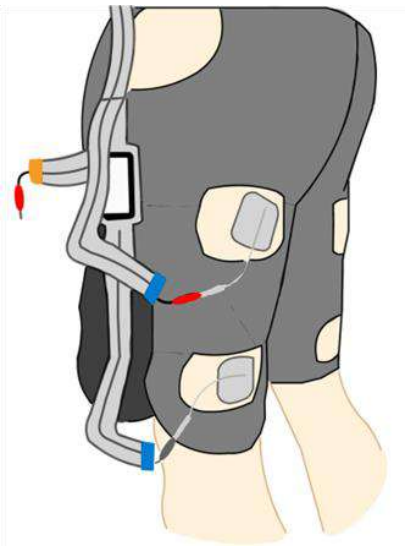


Figure 1 – Overview of the BioStim device, *in-situ,* as seen from the left rear

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Optimized Stimulation Patterns for FES-stimulated Cycling Using an Experimentally Identified Physiological Muscle Model

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Introduction: Functional Electrical Stimulation (FES) assisted cycling has demonstrated to be efficient in preventing physical function decline while increasing musculoskeletal health [1]. The stimulation parameters are frequently defined in a time-consuming procedure and experimentally tuned due to subject-specific biomechanical and electrophysiological characteristics. Numerical simulation can be used to explore stimulation patterns or advanced control strategies that generate optimized muscle forces and joint kinematics. In particular, trajectory optimization is an efficient method to explore novel control strategies, guided by the system's dynamics and task-related constraints. In this paper, a physiological FES-stimulated muscle model [2, 3], accounting for the calcium-troponin complex dynamics, is calibrated using experimental torque data from one participant with paraplegia. The personalized model is then used in a musculoskeletal pedaling simulation in which stimulation pulse durations are optimized using numerical optimal control.

Methods: One male participant with spinal cord injury (T6; AIS A) participated in the study. A commercially available recumbent tadpole trike (ICE Adventure, ICE, Falmouth, Cornwall, UK) was fixed on an instrumented cycling stationary trainer (KICKR Smart Trainer, Wahoo, Atlanta, Georgia, US) with the original crankset being replaced by a power-meter crank (2INPOWER, Rotor Bike Components, Madrid, Spain) to measure torque and pedaling power. Calf supports (HASE® Bikes, Waltrop, Germany) were fixed to the pedals to keep the ankle joint at 90° and restrict the leg movement to the sagittal plane. Isometric crank torques were recorded along the pedaling cycle at several knee angles (from 70° to 120° in 10° steps) first stimulating the *rectus femoris* and *vastus lateralis* muscles and then the hamstrings. The data obtained was used to solve a global trajectory optimization problem to identify the muscle parameters using the Bioptim software [4]. Then, the identified model was used in predictive simulation in which the stimulation pulse duration was optimized to produce a 15-Watt pedaling motion at 4.4 rad.s^{-1} (42 rpm).

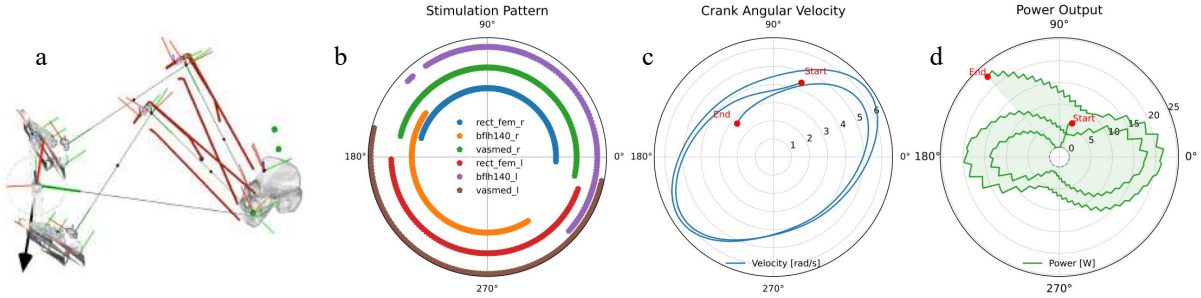


Figure **1**: a: Lower limb musculoskeletal model with FES-stimulated muscles; b: optimized stimulation pattern; c : resulting pedaling cadence; d : resulting pedaling power.

Results: Figure 1.a shows the lower limb musculoskeletal model used in the FES-assisted cycling simulations. Figure 1.b presents the stimulation pattern, highlighting the specific phases of the pedaling cycle during which each muscles is activated, over a 3-second simulation featuring coordinated agonist and antagonist activation. The resulting pedaling cadence was 4.5 ± 0.8 rad.s-1 (Fig. 1.c), and the corresponding power output was 10.2 ± 6.0 W (Fig. 1.d). Power output increased progressively over time, approaching a mean pedaling power closer to the target towards the end of the simulation

Discussion and conclusion: This study presents a first step towards improving the realism of FES-driven simulations and showcases the possibility of using physiological model-based control of FES-assisted cycling, with possible application in various other FES-assisted tasks

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MRI Spinal Cord Reconstruction Provides Insights into Mapping and Migration Following Percutaneous Epidural Stimulation Implantation in Spinal Cord Injury

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Background: Spinal cord epidural stimulation (SCES) has emerged as a promising intervention to restore motor functions following spinal cord injury (SCI). Effective SCES relies on precise spinal cord mapping to optimize stimulation configurations, aiming to restore standing and stepping abilities. This study investigates MRI spinal cord reconstruction as a complementary tool to guide SCES implantation and assess the impact of lead migration on mapping outcomes.

Methods: Two participants with SCI underwent percutaneous SCES implantation, beginning with a temporary (1-week, two-lead) trial followed by permanent, two-lead implantation [1]. Motor evoked potentials (MEPs) were recorded via electromyography (EMG) in response to 2 Hz stimulation with pulse durations of 250–1000 μs and amplitudes ranging from 1–14 mA. Pre-implantation T2 axial MRI images were used to retrospectively reconstruct the lumbosacral spinal cord segments (Figure 1). Discrepancies in MEP recruitment curves between temporary and permanent mappings were analyzed concerning lead positioning and migration.

Results: MRI reconstructions revealed suboptimal lead placement in both participants, with incomplete targeting of the L1-S2 spinal segments, contributing to observed discrepancies in MEP recruitment curves. In participant 0883, minor lead migration had minimal overall impact but resulted in reduced motor activity in the hip and knee muscle groups, suggesting that even subtle lead shifts can influence muscle recruitment. Differences in recruitment curve slopes indicated attenuated responses in specific muscles. In participant 0884, medial migration of the lead altered motor responses, necessitating higher stimulation currents to achieve comparable activation. The altered recruitment curves displayed inconsistent muscle activation and reduced motor evoked potentials in several muscle groups, underscoring the sensitivity of recruitment curves to changes in lead positioning. The MRI models demonstrated that even slight lead shifts can disrupt the balance of motor activation, reinforcing the critical role of anatomical precision in SCES mapping.

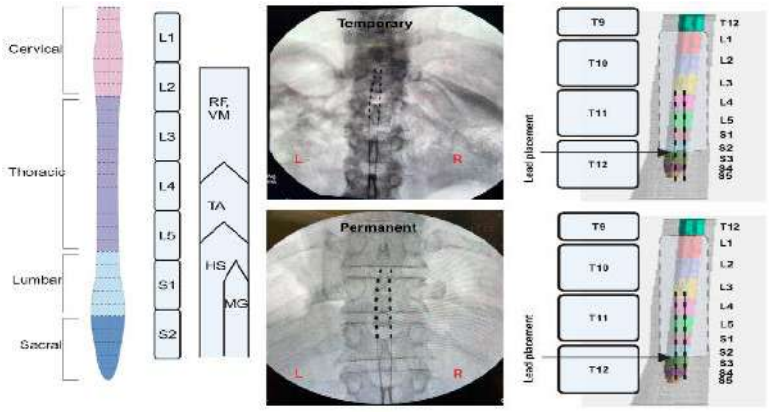


Fig 1. Temporary vs Permanent leads implantation in a participant with SCI

Conclusions: The MRI reconstructions enabled detailed comparisons between the intended and actual lead placements, helping to interpret inconsistencies in muscle activation patterns. Additionally, the study evaluated how subtle changes in lead positioning influenced the threshold currents needed to elicit motor responses and the distribution of activated muscle groups. This approach provides a quantitative framework to assess stimulation efficacy and the influence of anatomical variations on SCES outcomes. MRI spinal cord reconstruction provides further insight to SCES mapping by improving understanding of the role of adequate lead placement and impact of migration. Coupling temporary mapping with MRI analysis can enhance targeting accuracy for permanent implantation and help anticipate the functional consequences of lead migration.

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Optimal Control-Driven Functional Electrical Stimulation: a scoping review

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Introduction: Motor recovery following neurological disorders such as stroke and spinal cord injury remains a significant challenge. Among various methods, functional electrical stimulation (FES) presents a promising approach to restore functional motor control. However, FES effectiveness is often constrained by early muscle fatigue. This limitation can potentially be addressed through optimal control (OC), as optimized FES stimulation patterns could minimize muscle fatigue. This scoping review examines the applications and advancements of OC-driven FES, highlighting their impact and outlining directions for future research.
Methods: This scoping review adheres to the PRISMA-ScR [1] and JBI [2] guidelines. The Population-Concept-Context (PCC) framework encompassed healthy individuals and individuals with neuromuscular disorders receiving OC-driven FES during simulations, controlled experiments, or clinical trials. Articles containing the keywords "FES & OC OR fatigue" and all their synonyms were retrieved from six databases: Medline, Embase, Cinahl Complete, Web of science, ProQuest Dissertations & Theses Citation Index. Two authors (KC, MB) independently screened articles in two stages: (1) title and abstract screening, followed by (2) full-text screening, with a third author (FM) resolving any disagreements. Data extraction was performed by one author (KC) and validated by three others (FM, FB, MB).
Results: Of the 904 articles retrieved, 42 met the inclusion and exclusion criteria. They included 51 healthy participants and 30 individuals with neurological disorders, comprising 19 simulation studies and 23 experimental studies, but no clinical trial. Most studies focused on lower limb movements in the sagittal plane, employing musculoskeletal models with one or two degrees of freedom. Concerning FES models, no consensus was observed across studies about how modeling the muscle responses to electrical stimulation. Concerning cost functions, a tracking problem was used in 31 studies, involving musculoskeletal model parameters. Detailed cost functions representation is available in Figure 1.
Discussion and conclusion: This scoping review reveals that OCP is primarily applied to reduce muscle over-stimulation or manage multiple devices (e.g., FES combined with exoskeleton) by allocating control efforts. OCP enables the use of patient-specific FES models, but heavily depends on precise model identification, presenting significant clinical challenges in terms of implementation and feasibility. Overall, the field requires standardization efforts in computational methods and greater adoption of open science practices. Future research should prioritize on the development of FES models optimized for OC, enable real-time parameter identification, simulate complex motions, refine cost functions, incorporate symmetry and muscle synergies, and conduct clinical trials to validate findings.

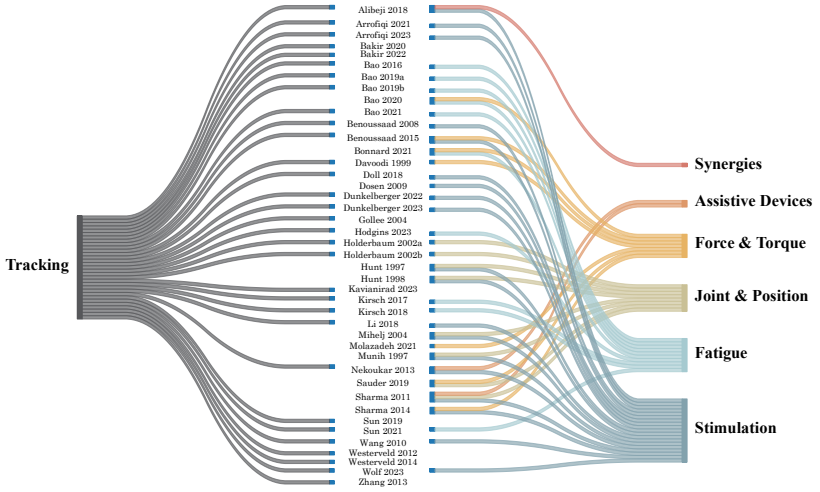


Figure **1**: Sankey Diagram: Relationships Between Scientific Articles and Their Cost Functions.

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Human-Like Stimulation Patterns through Reinforcement Learning for Muscle Fatigue Reduction in Functional Electrical Stimulation (FES)

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Introduction: Functional Electrical Stimulation (FES) is widely recognized as a critical tool for paraplegic rehabilitation, effectively reducing muscle atrophy. However, its efficacy is often limited by rapid muscle fatigue [1]. To address this limitation, researchers have explored strategies such as stimulation frequency adjustment [2] and Spatially Distributed Sequential Stimulation (SDSS) [3]. However, accounting for individual differences in muscle structure and usage patterns remains challenging, as these variations can significantly affect FES performance. To overcome this, reinforcement learning is employed in this study to develop adaptive stimulation patterns that reduce muscle fatigue.

Methods: This study focused on the rectus femoris, a primary muscle in the lower limbs, during an 8-minute FES leg extension task. Under fixed FES parameters (e.g., intensity, frequency, pulse width), 16 stimulation location patterns were tested, and the force output was measured using a load cell (CMA9839-50L, CAS Korea). Each stimulation location pattern was assigned a number, and the system was trained using Q-learning to adaptively learn the pattern with the smallest decrease in output. Two healthy male participants in their 20s completed the protocol.

Results: The results demonstrated that combining stimulation patterns significantly enhanced force output and reduced muscle fatigue compared to single-pattern stimulation. Subject 1 achieved best results with combination of Patterns 10 and 0 (Fig. 1), while Subject 2 performed best with a combination of Patterns 6 and 0 (Tab. 1). The adaptive learning approach enabled the system to dynamically adjust policies in real-time, highlighting the effectiveness of tailored stimulation combinations for FES applications.

Discussion and conclusion: The adaptive stimulation location patterns developed in this study achieved improvement in peak force while significantly reducing muscle fatigue compared to traditional methods (Tab. 1). The results revealed that the stimulation location patterns that reduce muscle fatigue varied between participants, reflecting the challenges of individual differences in muscle structure and usage noted in the introduction. These findings underscore the need for further research on electrode location optimization and advanced machine learning models to effectively reduce muscle fatigue in FES applications. This approach demonstrates the potential for personalized and adaptive stimulation strategies to address individual differences and significantly enhance rehabilitation outcomes.

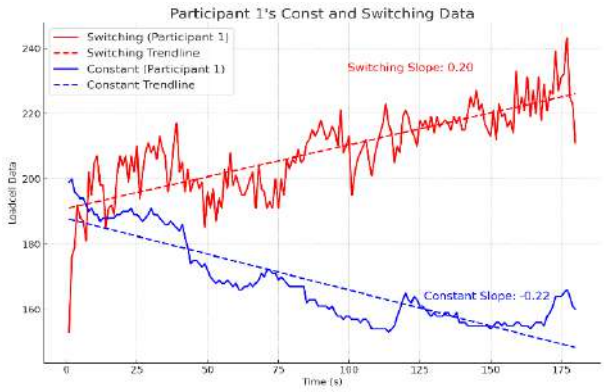


Figure **1**: Force-Time Curves for participant 1's Based on Patterns

Table 1: Comparison of Constant and Best Switching Conditions for Each Participant

Participant (Condition)	Peak Force Increase (%)	Slope	Slope Angle (°)
Participant 1(Constant)	-	-0.22	-12.41
Participant 1(10-0 Switching)	21.5	0.20	11.31
Participant 2(Constant)	-	-0.10	-5.71
Participant 2 (6-0 Switching)	82.8	0.19	10.76

Acknowledgments: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT).(No. NRF-2021R1A2C2008379) We thank InBody for their support and the members of Team BeAGain for their dedication and contributions.

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ENHANCING SEATED POSTURE AND NECK RETRACTION VIA EPIDURAL SPINAL CORD STIMULATION AFTER A MOTOR COMPLETE SPINAL CORD INJURY: A CASE STUDY

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Introduction: Epidural spinal cord stimulation (eSCS) has been able to facilitate partial recovery of standing and stepping ability when implanted over the lumbar enlargement of the spinal cord after a motor complete spinal cord injury (SCI) [I]. However, no studies to date have examined the impact of eSCS on improving postural control through changes in kinematics and electromyography (EMG) after a complete SCI. This study assessed, for the first time, the impact of eSCS applied at a low thoracic level on modulating postural control after a complete high thoracic SCI.

Methods: The study involved one participant with SCI (AIS A, T2, 7 years post injury) who had two implanted Medtronic Intellis eSCS paddle leads to manage chronic neuropathic pain. The upper lead spanned vertebral segments T5-T7 and the lower lead spanned segments T8-T10. After three eSCS mapping sessions in which 16 channels of EMG activity from the trunk and lower extremities was recorded, we chose to use the T8-T10 paddle lead with an optimized configuration of 3-, 8-, 14-, 10+ at 1000 µs pulse width and 60 Hz, as it produced the greatest postural/neck retraction. Six trials for both eSCS off/on conditions were then performed for a natural seated task while recording kinematic activity of the back and neck and EMG activity. The participant then performed a cervical rotation task for eSCS on/off conditions where they were asked to turn their head 8 times per side per condition.

Results: For the natural seated task with eSCS on, there was an average change in the anterior/posterior maximal head angle by 17.84 ± 2.75°, the neck angle by 5.01 ± 2.26°, and the thorax angle by 12.97 ± 1.65°. During the natural seated task there was no significant activation between eSCS off/on for muscles above the T2 level of injury. However, the eSCS on compared to the eSCS off was significant for the left ($p < 0.0001$) and right ($p < 0.0001$) erector spinae muscles at T9, the left ($p < 0.0001$) and right ($p < 0.0001$) erector spinae muscles at T3, the left ($p = 0.0248$) and right ($p = 0.0338$) trapezius, the left ($p = 0.018$) and right ($p = 0.0167$) rhomboids, and the left upper pectoralis ($p = 0.0003$). There was no significant change in the cervical rotation conditions between the eSCS off/on condition in the head, neck or thorax angles.

Discussion/Conclusion: This study exhibits, for the first time, the impact of eSCS applied below the level of a complete injury on modulating neural pathways above the level of injury. The knowledge regarding the changes in biomechanics and EMG muscle activity during eSCS is critical, as it indicates that eSCS could be used as a tonic rehabilitative intervention that promotes greater seated trunk control. These abilities are essential in maintaining autonomy and may potentially mitigate complications arising from having poor posture.



Figure 1. Changes in posture with eSCS off (left)/on (right)

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THE EFFECT OF TRANSCUTANEOUS SPINAL CORD STIMULATION ON PROPRIOCEPTION

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Introduction: Transcutaneous spinal cord stimulation (tSCS) is a neuromodulation technique that has gained considerable attention for its potential to improve upper-limb motor function recovery following spinal cord injury [1]. Despite these proemising prospects, the specific effects of tSCS on neural pathways and the mechanisms underlying movement restoration remain largely unclear. Considering the crucial role of proprioception in motor control, we hypothesized that the motor improvements induced by tSCS are linked to enhanced proprioceptive function. To investigate this hypothesis, we conducted a preliminary study assessing the impact of tSCS on proprioception by having participants complete proprioception-dependant tasks using the KINARM exoskeleton.

Methods: We recruited participants with incomplete cervical SCI classified as AIS C or D ($n_{SCI} = 5$) and neurologically intact (NI) controls ($n_{NI} = 10$). Stimulating electrodes were placed over the C3-C4 and C6-C7 spinal segments, with return electrodes on the iliac crests. Single stimulus pulses were delivered to determine the spinal evoked potential threshold in the left biceps brachii muscle using lectromyography (EMG). These participants were then asked to perform two tasks: Position Matching, where the KINARM exoskeleton guided the non-dominant arm to 9 target positions, mirrored by the dominant arm (6 random repetitions per position), and Arm Movement Matching, where the exoskeleton moved the non-dominant arm between 3 target positions, mirrored simultaneously by the dominant arm (36 trials). In both tasks, participants rely on proprioceptive feedback from their non-dominant arm to guide their movements.Tasks were each performed twice—once with tSCS administered continuously from task initiation through completion (including mirroring), and once without stimulation.. Stimulation was delivered at a frequency of 40 Hz with 1 ms pulses containing a 10 kHz carrier frequency. The amplitude of stimulation was identified as the threshold for evoking the spinal evoked potential in the biceps brachii muscle.



Figure 1: Electrode placement and stimulation parameters.

Results: In the position-matching task, tSCS increased lateral errors (difference between optimal and performed points in the x-axis) in neurologically intact participants and vertical errors (difference in y-axis) in individuals with spinal cord injury (SCI) (both $p = 0.02$). In the arm movement task, tSCS enhanced performance in SCI participants by reducing offset delays ($p = 0.03$) and producing smoother movements, evident by fewer peaks in movement speed ($p = 0.01$).

Discussion and Conclusion: Our study indicates that tSCS significantly affects the proprioceptive sense in the arms, with different impacts on individuals with SCI and neurologically intact controls. The enhanced performance in movement tasks among participants with SCI suggests that tSCS may improve proprioceptive feedback and motor control, potentially aiding rehabilitation efforts. These findings support the idea that tSCS could be a valuable tool in enhancing functional recovery after SCI by modulating sensory pathways. Further research is necessary to understand the mechanisms involved and to optimize stimulation protocols for clinical applications.

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SCALABLE DESIGN OF DRY, FLEXIBLE TEXTILE ELECTRODES IN USER-FRIENDLY ADJUSTABLE SLEEVE

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Introduction: Complex neuroprosthetic systems have been developed to regulate balance in individuals with spinal cord injury (SCI) through a closed-loop system. Since these systems are designed to perform functional electrical stimulation (FES) on various muscle groups simultaneously, many electrodes are required to be placed during therapy. This is a cumbersome process that takes a significant amount of time, and it is not able to be done easily by those with limited dexterity. Textile-based electrodes attempt to address this issue by allowing the user to place many electrodes simultaneously by having multiple electrodes pre-positioned in one piece of clothing. However, most of these textile-based electrodes are required to be used wet to deliver comfortable stimulation [1], and their ability to withstand laundering has not been adequately evaluated [2]. Moreover, existing textile-based electrode designs do not account for the accessibility needs of the end-users. Garments with textile-embedded electrodes often take the form of compression clothing to ensure adequate electrode-skin contact, making it difficult to use by those with SCI due to the tightness of the garment [3]. Furthermore, the process for connecting each individual electrode to the stimulator must also be streamlined for potential end-users to utilize these systems with ease. Thus, we were motivated to develop a new electrode material and garment design to address these challenges which could perform equivalently to existing options.
Methods: We manufactured and characterized the mechanical and electrical properties of a dry electrode material that can be permanently attached to a garment using a commercial heat press. Experiments are currently ongoing to verify the performance of these new electrodes during stimulation compared to standard self-adhesive hydrogel electrodes with able-bodied participants, as well as to verify their robustness following numerous washing cycles.
Results: When compared to other dry electrode materials, the new electrode material was found to be very flexible and stretchable, making it better suited to conform to the skin, as well as having similar electrical properties. A prototype sleeve has been developed for the lower leg that is fully adjustable to accommodate different sized and shaped legs which can be easily tightened/loosened to enable ease of donning/doffing the garment. In addition, a connector has been designed to attach to the garment to connect many electrodes to the stimulator at once, while requiring limited force to attach or remove the connector from the garment.
Discussion and conclusion: The development of a dry, flexible, and stretchable electrode material that can be easily integrated into garments addresses several limitations of current textile-based electrodes. The result of this prototype sleeve is a basis for which a garment for the lower limbs can be developed for use with not only complex standing neuroprosthesis, but also any FES applications for the lower limbs.



Figure **1**: Interior of garment showing dry electrode surface to be in contact with skin

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THE ROLE OF CUTANEOUS SENSORY AFFERENTS IN MODULATING SPINAL COTD NEURAL PATHWAYS DURING CERVICAL LEVEL TRANSCUTANEOUS SPINAL CORD STIMULATION

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Introduction: Spinal cord injuries (SCI) disrupt the communication between the central nervous system and the peripheral nervous system, affecting sensorimotor functions. Rehabilitation for SCI is crucial for restoring motor function and improving quality of life. Non-invasive transcutaneous spinal cord stimulation (tSCS) has emerged as a promising neuromodulation therapy that could aid rehabilitation by engaging spinal neural networks [1]. Computational modeling indicates that tSCS activates similar pathways to those targeted by epidural spinal cord stimulation (eSCS) [2]. However, current models do not fully account for the influence of cutaneous afferent inputs that are likely activated during tSCS. This study investigates the role of cutaneous sensory afferents in modulating spinal circuitry during tSCS by altering afferent inputs effect using topical anesthesia.

Methods: Twelve volunteers without neurological impairments (5 males and 7 females) enrolled for this study. Versapro sham cream used for 30 mintues to have consistent skin impedance before start the experiemnt to the skin overlaying the cervical level. Following that, the cream was removed before placing electrodes at cervical levels C3-4 and C6-7 to apply tSCS using DS8R stimulators (Digitimer, Welwyn Garden City, UK). We measured two-point discrimination (cm), the current amplitude of tSCS at the threshold of the initial sensoy perception(mA) and maximum tolerable amplitude current of tSCS (mA) to assess the quality of anesthesia cream before and after anethesia cream application. Benzocaine 20%, Lidocaine 10%, and Tetracaine 4% (BLT) cream was applied to anesthetize the skin for 30 minutes. Additionally, we recorded the stimulation amplitudes required to elicit threshold spinal evoked potentials (SEP) in the biceps brachii (BB) muscle both pre- and post-BLT to assess changes in neural excitability. The stimulation intensity was set at a low level, just sufficient to evoke a minimal reflex response in the BB muscle. Such low-intensity stimulation preferentially recruits large-diameter sensory afferents via the dorsal roots, leading to transsynaptic activation of spinal motor pools[1]. A 1-ms long tSCS stimulation was delivered to the cervical region using DS8R stimulators (Digitimer, Welwyn Garden City, UK). The surface Ag-AgCl EMG electrodes was positioned on the belly of BB muscle of the left arm to record muscle activiy.

Results: The findings demonstrate that reducing sensory input through topical anesthesia significantly affects sensory perception. The amplitude of tSCS stimulation for sensory perception threshold, sensory maximum tolerance and distance of two-point discrimination significantly increased after BLT application. Additionally, to elicit the identical amplitude of SEP after applying topical anesthesia showed a significant increase in the required tSCS stimulation amplitude.

Discussion and conclusion: This research provides the pontial for optimizing tSCS parameters based on cutaneous sensory afferents to have the most effect from rehabilitation after neural injuries.

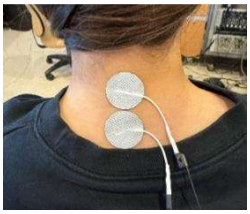


Figure 1: tSCS Electrode placement over C3-4, C6-7 of spinal cord.

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COMPARING THREE DIFFERENT SPINAL CORD STIMULATION MODALITIES FOR RESTORING WALKING AFTER SPINAL CORD INJURY

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Introduction: Spinal cord injury (SCI) may cause severe disruption to body functions such as locomotion [1]. Spinal cord stimulation (SCS) is a promising approach for restoring walking by reactivating locomotor networks below the injury. This study investigates the efficacy of three SCS modalities—epidural spinal cord stimulation (eSCS), intradural spinal cord stimulation (iSCS), and intraspinal microstimulation (ISMS)—with a focus on determining the most effective approach for eliciting functional overground walking patterns. By evaluating each modality independently, this work seeks to provide guidance for optimizing SCS techniques that enhance locomotor recovery following SCI.

Methods: We designed a 16-channel custom-tailored implantable electrode array for both epidural and intradural stimulation, specifically for the cat lumbar enlargement. To ensure compatibility with the cat model (e.g., subdural space), the array had a total thickness of 100 microns. For epidural stimulation, the array was placed over the dura mater covering the lumbar enlargement and for subdural stimulation, it was placed subdurally covering the same region. ISMS involves the precise insertion of 16 microwires into the spinal cord to target locomotor-related networks in the ventral horn [2, 3]. Experiments were conducted in deeply anesthetized cats, which were placed in a sling that supported their head and trunk while the legs moved freely over an instrumented walkway. A unified controller paradigm was employed for the delivery of SCS across the 3 modalities. A custom MATLAB algorithm was used to control the stimulation, and data collection included ground reaction forces, angular joint velocity, and motion capture [4].

Results: Results: Magnetic resonance images of the extracted spinal cords revealed no evidence of compression or distortion due to the epidural and intradural arrays or ISMS electrodes. Preliminary kinematic data showed that ISMS facilitated a near-normal walking pattern with 4 primary synergies (forward reach, downward extension, backward propulsion, upward flexion), while eSCS and iSCS primarily produced 2 synergies (propulsion and flexion) with limited grading. Quantitative analysis reflected these differences: ISMS-evoked movements showed smoother ground reaction force profiles (peak GRF: 3.5 ± 0.7 N) and joint angular range closer to physiological walking (knee: 29.1 ± 0.2 °), while eSCS (7.6 ± 1.6 N, 63.6 ± 1.8 °) and iSCS (7.3 ± 1.5 N, 59.9 ± 0.8 °) generated less coordinated responses.

Discussion and conclusion: These preliminary results demonstrate the ability of ISMS to more precisely target the locomotor-related networks in the spinal cord, potentially achieving more natural and coordinated restoration of walking after SCI when compared to eSCS and iSCS. Future work should focus on comparing the distance that can be walked using each modality. Detailed analyses of the stimulation amplitudes and energy expenditure for each modality are also needed.

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cFOS ACTIVATION AFTER EPIDURAL SPINAL CORD STIMULATION

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Introduction: Spinal cord injury (SCI) profoundly impacts an individual's function and quality of life with significant impairments in standing and walking often cited as top priorities for individuals with paraplegia [1]. Epidural spinal cord stimulation (eSCS) has emerged as a promising approach to address these deficits by electrically activating locomotor networks to facilitate functional movements, including standing and walking [2]. Despite its therapeutic potential, the precise neural activation patterns induced by eSCS remain largely unexplored. Additionally, unexpected cellular-level responses, such as lack of ventral horn neuronal activity, have been observed in our porcine model, prompting the need for further investigation. This study aims to investigate the distribution of neural activation following eSCS and evaluate the potential effects of different anesthetic agents on this activation.

Methods: Ten female domestic pigs were assigned to two anesthetic treatment groups: propofol (n=5) and pentobarbital (n=5). Following a laminectomy to expose the L3 to L5 spinal cord segments, each animal underwent three hours of eSCS. The spinal cords were subsequently extracted for immunohistochemical analysis. Tissue sections were stained for cFos, a protein marker of neural activity, and NeuN, a neuronal marker, to assess the distribution of neural activation [3,4]. Fluorescent imaging was conducted, and cFos-positive cells were counted by three researchers blinded to the group allocation of the spinal tissue. Regions within the spinal cord sections were divided based on Rexed's laminae, and comparisons of the numbers of cFos positive neurons were made across these different regions and between the two anesthetic groups [5].

Results: Preliminary data indicate a reduced number of cFos-positive neurons in the propofol group compared to the pentobarbital group, particularly in the ventral regions (laminae 7-9). Overall, cFos-positive neurons following eSCS were predominantly concentrated in the dorsal horn (laminae 1-4), with activation extending into intermediate regions (laminae 5-6 and dorsal 7), and less activation observed in the ventral horn (laminae 7-9).

Discussion and Conclusion: Our findings suggest that the choice of anesthetic agent may influence cFos expression following eSCS, aligning with previous studies in other animal models [6]. Propofol and pentobarbital both act at the $GABA_A$ receptor, and it has been suggested that they have similar mechanisms of action [7]. However, propofol anesthesia cannot be used for individuals with mitochondrial disease while pentobarbital can, indicating there are differences between the two anesthetics [8]. The conflicting information regarding mechanism of action indicates further work is needed to understand why the cFos expression is different under different anesthetic protocols. These results underscore the importance of considering anesthetic choice in preclinical studies, particularly when assessing neural activation as a primary outcome.

Additionally, this study provides information about the acute activation pattern induced by eSCS, with predominant activation in the dorsal horn and some propagation into intermediate and ventral regions. Future research will focus on comparing these findings with other spinal cord stimulation techniques and exploring the effects of chronic eSCS to better understand the induced neural plasticity and its therapeutic potential.

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AN ALTERNATIVE PROPHYLAXIS FOR DEEP VEIN THROMBOSIS USING INTERMITTENT ELECTRICAL STIMULATION.

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Introduction: Deep vein thrombosis (DVT) is a significant contributor to the global disease burden, and the annual incidence of DVT is 1–2 cases per 1,000 people in the general population [1]. A major contributing factor for DVT is venous stasis which in current practice is commonly managed by pharmacological anticoagulation medications and mechanical prophylactic devices like intermittent pneumatic compression (IPC). Nonetheless, there are issues related to IPC including discomfort, lack of portability and reduced patient mobility which results in low patient compliance especially in non-hospitalized patients [3]. Intermittent electrical stimulation (IES)[4] applied to the muscles of the legs offers an innovative alternative for enhancing venous blood flow[5] and reducing the risk of thrombosis. This study investigated the changes in blood flow in the deep venous system caused by muscle contractions in the legs induced by IES.

Methods: Venous velocity and blood flow in both the popliteal and femoral veins were measured using Doppler ultrasound during IES-induced contractions in 32 participants (22 typical/healthy, 10 post-stroke). The patented stimulation pattern consisted of 1s-long bouts of 40Hz, 300µs-long biphasic pulses, delivered sequentially to the gastrocnemius and tibialis anterior muscles, with a 2 minute-resting phase between each sequence of bouts through 7.5 x 10 cm electrodes. A custom-built apparatus (Fig. 1) recorded plantar and dorsiflexor contraction forces with participants seated in a semi-recumbent position.The magnitude of the plantar flexor forces evoked by IES were normalized to the maximum voluntary contraction (MVC) of the plantar flexors produced by typical study participants, or the maximal plantar flexor force (MPF) that could be produced by electrical stimulation without discomfort in participants with stroke. The relationship between strength of plantar flexor muscle contraction induced by IES and increases in popliteal and femoral venous velocity was analyzed.

Results: IES significantly increased venous velocity in both typical and post-stroke participants (Fig. 2). In typical participants, popliteal peak venous velocities increased by 8 times relative to baseline, respectively, at plantar flexor contraction levels of 11–20% with proportional increases in femoral vein velocity. Post-stroke participants achieved a 5.9-fold increase in popliteal venous velocity at moderate contraction levels (51–60% MPF) and no muscle fatigue was observed. Participants expressed a high degree of comfort with extended IES use, including during sleep.



Figure 1: The custom-built apparatus

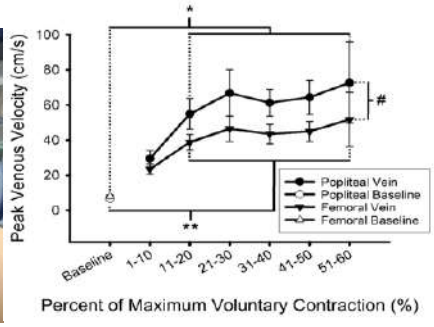


Figure 2: The PVV Vs MVC

Discussion and Conclusion: IES may present a solution addressing the portability and mobility issues while potentially providing additional benefits such as preventing muscle atrophy. The limitations of pharmacological solutions like anticoagulants in some patients further highlight the need for such mechanical interventions. This study demonstrates IES's ability to enhance venous hemodynamics by increasing venous velocities in the deep venous system throughout the lower limbs, even in populations at high risk of DVT. These findings support IES's potential as a practical and patient-friendly mechanical intervention for DVT prophylaxis. We have developed a device called the SOCC^{TM} (Smart Ongoing Circulatory Compressions) for delivering IES in

hospitalized study participants and are currently planning studies for assessing its safety, feasibility and acceptability.

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ORTHOTIC AND ACUTE EFFECTS OF FUNCTIONAL ELECTRICAL STIMULATION THERAPY ON STANDING BALANCE IN INDIVIDUALS WITH SPINAL CORD INJURY

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Introduction: Functional electrical stimulation (FES) therapy is widely used for upper limb rehabilitation, but its application for enhancing standing balance remains limited, with the underlying mechanisms still underexplored. We have developed a novel FES therapy aimed at improving standing balance by incorporating closed-loop controlled FES to the ankle muscles during visual feedback balance training (VFBT) [1,2]. Preliminary findings have shown the feasibility and positive therapeutic effects of combining FES with VFBT in five individuals with iSCI [3,4]. Here we aimed to investigate the orthotic and acute effects of FES on standing balance performance, as well as its impact on neuroplasticity, to better understand the neuromechanical effects of FES therapy.

Methods: Sixteen able-bodied individuals and 11 participants with chronic motor incomplete spinal cord injury (iSCI) participated. Each participant underwent two sessions of visual feedback balance training (VFBT)—one with FES (FES+VFBT) and one without (VFBT alone)—scheduled in a randomized order at least 48 hours apart. To test the orthotic effects, standing performance, including static and dynamic balance tests, was assessed and compared between the two conditions. To test the acute effects, motor evoked potentials (MEP) elicited by transcranial magnetic stimulation were measured to assess corticospinal excitability in the soleus and tibialis anterior muscles. Spinal excitability was also evaluated using soleus F-waves before and after each session.

Results: No significant differences were observed in static and dynamic balance performance between the two conditions. Similarly, ankle joint stiffness during the static balance test showed no notable differences between conditions. These results show that there was no detectable orthotic effects. However, on the acute effects, MEP results revealed a significant increase in soleus MEP amplitudes following FES+VFBT compared to VFBT alone for the combined groups ($36.1 \pm 41.5\%$ vs. $0.461 \pm 26.2\%$, $p < 0.001$) . No significant changes were found in tibialis anterior MEP amplitudes for the combined groups ($55.2 \pm 94.3\%$ vs. $13.1 \pm 47.0\%$, $p = 0.077$). In participants with iSCI, soleus F-wave amplitudes were significantly elevated after FES+VFBT compared to VFBT alone ($48.4 \pm 77.6\%$ vs. $-9.69 \pm 44.8\%$, $p = 0.003$). This trend was not observed in able-bodied participants ($5.78 \pm 51.6\%$ vs. $-3.78 \pm 25.1\%$, $p = 0.507$).

Discussion and conclusion: These findings suggest that combining VFBT with FES significantly enhances corticospinal excitability of the plantarflexors within a single session. In individuals with iSCI, these neuromodulatory changes appear to be partially mediated by increased spinal excitability.

In conclusion, while body movement metrics did not exhibit significant changes, the study highlights the potential of FES to induce neuromodulatory effects, particularly enhancing spinal and corticospinal excitability. These results emphasize the importance of neuromodulation over motor learning through advanced movements in achieving therapeutic benefits.

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A method to improve sensory recovery following median/ulnar nerve repair using transcutaneous electrical stimulation

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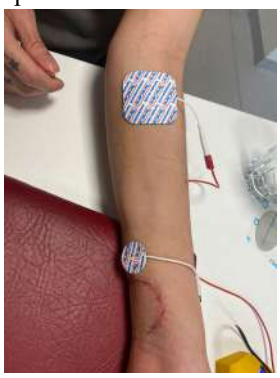
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Introduction: The median, ulnar, and radial nerves supply the hand, with the radial nerve primarily motor and the median and ulnar nerves serving both motor and sensory functions. These latter nerves control intrinsic hand muscles and relay sensory input from the palm and fingers, critical for normal hand function. Injury to the median or ulnar nerves are not uncommon and, even if sutured with microsurgical technique, always result in impaired hand function [1]. Such injuries halt nerve signalling, prompting cerebral adaptations. Research done in this field highlights the importance of early stimulation of deafferented sensory and motor brain areas during rehabilitation [2]. Transcutaneous electrical stimulation (TES) has the potential to induce action potentials in the axons of injured nerves, transmitting signals to the central nervous system (CNS) in a manner that mimics natural physiological processes. Recent studies have shown that early and consistent activation of these cortical regions using ES can prevent maladaptive reorganization and improve functional outcomes after nerve repair [3]. This study focuses on leveraging TES to enhance nerve rehabilitation and optimize sensory recovery.

Methods: A custom-built electronic stimulator was developed to deliver biphasic, charge-balanced, current-controlled pulses. The cathode electrode was positioned over the median or ulnar nerve, proximal to the injury (Fig 1a). The stimulation protocol consisted of 5-second bursts of pulses alternating with 5-second pauses. The parameters of each burst—pulse amplitude and frequency—were randomized within a predefined, patient-specific range. Frequencies were spaced exponentially between 2 Hz and 100 Hz, while pulse amplitudes could be adjusted by the patient across four levels using a linear slider on the stimulator. The study included four patients: three with ulnar nerve injuries and one with a median nerve injury, all at wrist level. Each patient used the device daily for 30 minutes over a six-month period, starting within two weeks after nerve repair. Sensory-motor recovery was assessed using a comprehensive battery of clinical tools, including the Semmes-Weinstein monofilament (SWM) test, two-point discrimination (2PD) test, Sollerman test, manual muscle test, Jamar dynamometer, and a pain/discomfort test, as described by Rosén et al. [4].

Results: The clinical tests conducted within the first six months of rehabilitation showed that most of the patients and most of the measures fell within the range of scores previously reported by Rosén et al. [4]. For example, Fig. 1b illustrates the SWM test results for the four patients. As shown, the sensory reinnervation rate aligns with the previously reported range (shaded area).

Discussion and conclusion: This ongoing clinical study is evaluating the potential of electrical stimulation to enhance nerve rehabilitation following injury. Although the patients self-reported perceived benefits of using electrical stimulation, such as reduced pain, the majority of clinical results after six months—more than five months of electrical stimulation—do not indicate a significant effect of this therapy in comparison to standard treatment. However, a one-year follow-up will be conducted to assess any delayed effects of this intervention.



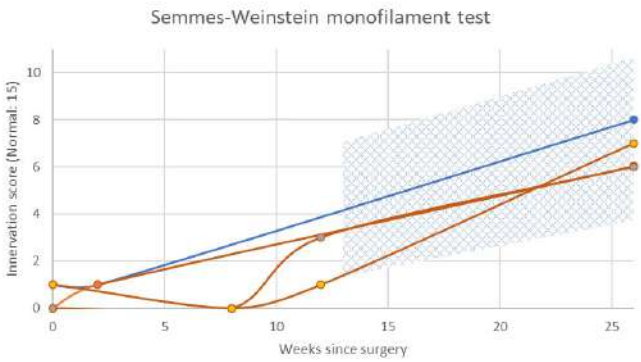


Figure 1: a) Stimulation setup during the nerve rehabilitation protocol, b) SWM test results. Median (blue) and Ulnar (orange) nerve re-innervation rate fall within the range previously reported [4].

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THIN-FILM MICROELECTRODE ARRAYS FOR RECOVERY OF MOVEMENT AFTER SPINAL CORD INJURY

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Introduction: Intraspinal microstimulation (ISMS) is a neuromodulation technique targeting the lumbar spinal cord's locomotion control centers showing in several animal studies the potential for restoring mobility after spinal cord injury (SCI) [1]. However, translation of ISMS to clinical implementation after SCI in humans is challenging. Challenges include the foreign body response to the chronically implanted array [2,3], targeting locomotor-related networks accurately, and microelectrode dislodgement due to spinal cord movement [4]. In this work we developed a flexible, thin film implant with a small cross section to reduce the long-term scar tissue formation. Additionally, we equipped each arm with multiple stimulation sites to improve implantation targeting. We also incorporated strain-relief structures to enhance long-term mechanical stability of the implant. We then characterized device electrochemical properties and assessed feasibility of implantation and acute functionality in a clinically relevant animal model—domestic pig.

Methods: Arrays were fabricated using standard nanofabrication techniques [5] and consisted of a polyimide (PI) base, metal interconnects, and passivation PI layers with exposed sputtered iridium oxide film (SIROF) stimulation sites. Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT) was electrochemically deposited on the stimulation sites to enhance charge injection capacity. Serpentine structures were incorporated in each implant arm and the array's main body for strain-relief (Fig. 1A). Arrays were fabricated with either 3 or 7 implant arms per spinal cord side, each containing three stimulation sites, yielding 18 and 48 channels, respectively. The electrochemical properties of the active sites were evaluated by measuring voltage drop as a result of biphasic current pulses in phosphate buffer solution (PBS). Prior to the implantation, implant arms were attached to a tungsten insertion aid using polyethylene glycol (PEG) and the insertion aids were secured to a holder placed on top of the spinal cord. Implantation was tested in vitro in 0.6% agarose gel and in a freshly euthanized pig spinal cord. The functionality of the 18-channel device was tested in an anesthetized pig in which the devices were implanted, and kinematics and isometric forces were recorded at stimulation amplitudes from 25µA to 300µA (train biphasic symmetrical pulses at with 200 µs pulse width at 50Hz for 0.5 s)

Results: The ISMS array successfully evoked lower-limb movements. Four out of six implanted arms (11/18 active sites) generated movements including bilateral hip flexion and knee extension. Increased stimulation amplitude produced a graded increase in joint range of motion and isometric forces, suggesting transsynaptic activation of motor neurons in the ventral gray matter. Different activation sites in each implanted arm evoked similar movements with varied magnitudes. Post-mortem MRI scans revealed placement of the 2 implant arms in the ventral spinal cord.

Discussion and Conclusion: This study demonstrates the feasibility of implanting a flexible, thin-film ISMS array in large animal models, evoking motor responses that could support functional walking. The design may reduce strain and foreign body response while increasing the amount of stimulation sites for better targeting. Further preclinical testing, including chronic studies and immunohistochemical assessments, to evaluate long-term tissue response and electrode stability, are necessary. This work advances ISMS technology toward human applications for restoring walking after severe SCI.

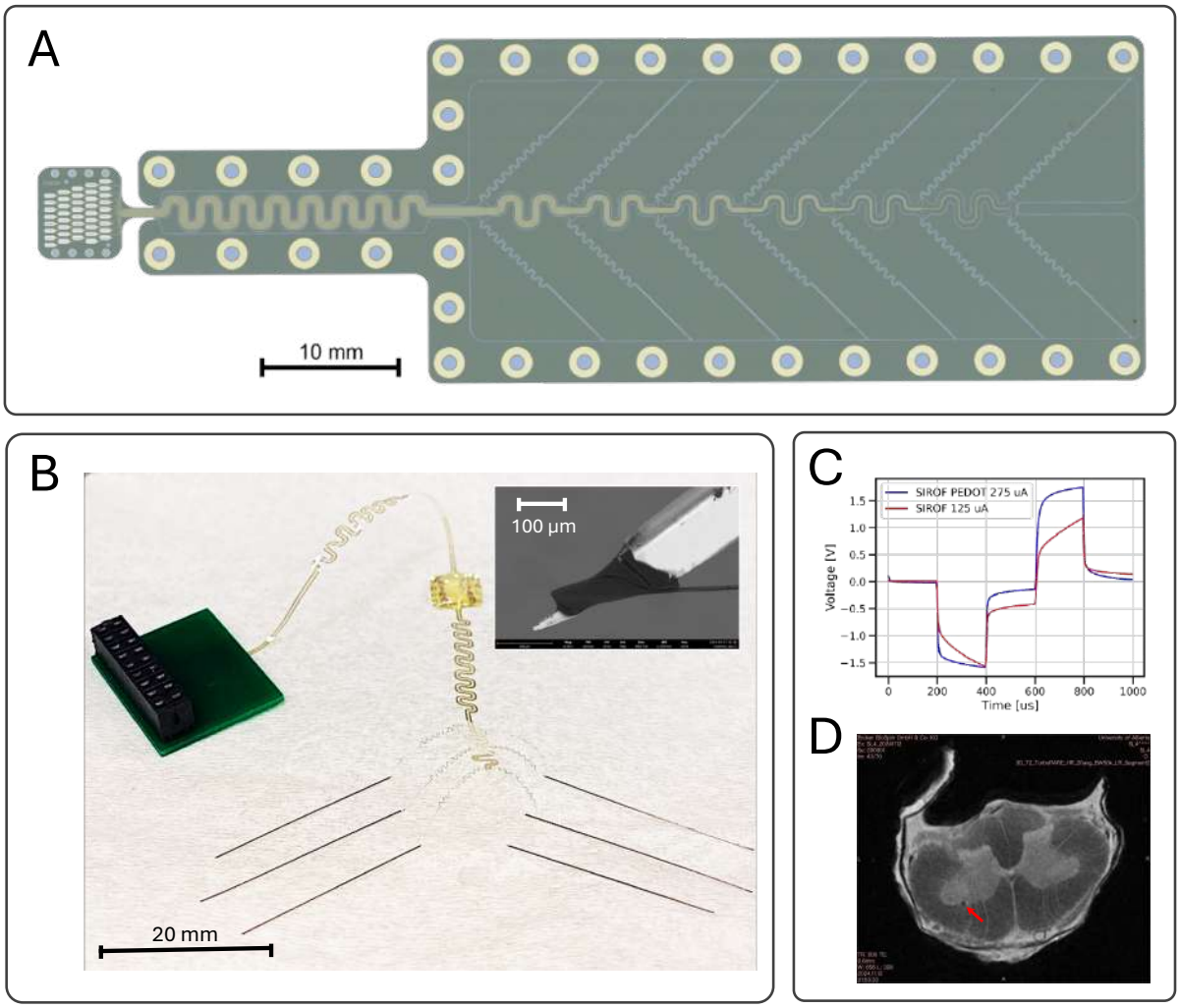


Fig 1. A) 48 channel ISMS array on the silicon wafer. B) 18 channel ISMS array with insertion aids pre-attached to each arm. Inset shows scanning electron microscopy of the microelectrode attached to insertion aid with PEG. C) Voltage response of SIROF and PEDOT microelectrodes to 125µA and 275µA current pulses, respectively. D) MRI image showing the location of an implanted microelectrode in the ventral spinal cord.

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Image Processing of X-rays of the Lumbar Spine and Spinal Cord Stimulation Implants

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Introduction: Neural injuries, such as spinal cord injury (SCI) and stroke, lead to significant motor impairments affecting individuals' quality of life. Motor neuro-prostheses can vastly improve rehabilitation outcomes and increase independence and mobility. Spinal cord stimulation (SCS) has been FDA-approved for chronic pain management [1] and is currently being investigated in clinical trials for the rehabilitation of upper and lower-limb function after neural injury, with a large majority of applications aiming to improve gait recovery [2].
Electrode location is determined intraoperatively using fluoroscopy, with confirmation of electrode location relative to the vertebral segments in X-ray images. We aim to correlate the anatomical electrode location with the functional output, measured as muscle activity using electromyography (EMG). However, current methods of manually identifying lead placement relative to the spinal vertebral level via X-ray images are time-consuming and prone to inaccuracies. This compromises the ability to accurately correlate muscle activity from EMG with the location of the corresponding SCS electrode. To overcome this challenge, we propose to use image analysis and machine learning methods to automate the identification of electrode location relative to the spinal vertebral level.

Methods: We searched through medical records from 73 patients who received SCS implant in the thoraco-lumbo-sacral region to generate an image dataset of 209 X-ray images. The dataset was used to train a U-Net model, which is a type of convolutional neural network. The U-Net was used to segment vertebrae T7-12 and L1-5, as well as individual SCS electrodes from the X-ray images **(Fig. 1).** We trained the U-Net model using the Adam optimizer with an initial learning rate of 1×10^{-3} over 50 epochs. We evaluated the performance of the trained U-Net model using a testing subset (20%) of images to ensure generalizability, with fine-tuning as needed to improve performance.



Figure 1: Pixel Annotated X-ray of the Lumbar Spine with Implanted Electrodes. Different colors represent distinct groups or structures labeled for identification by a U-Net model.

Preliminary Results: Before accessing the larger dataset, we initially trained the model using 6 X-ray images. The accuracy on this small subset of images over 50 iterations was 29%. While these preliminary results are encouraging, we anticipate that accuracy will significantly increase with the use of the entire dataset in the training process. There are 1,900 additional patient records to be screened for inclusion in the full dataset. The expanded dataset will improve the model's segmentation capabilities by increasing the diversity of training images, enabling the model to better accommodate variations in patient anatomy.

Discussion and conclusion: The trained U-Net model will be essential for future intraoperative testing, where we will record muscle activity from the leg muscles using EMG during SCS. It will facilitate the correlation of the anatomical position of the electrodes with the muscle activity from EMG, allowing us to automatically construct a functional map of muscle activation in response to SCS. As SCS becomes more widely used as a rehabilitation intervention, the need for creating a functional map between electrode location and muscle responses will increase. This work will be a valuable tool for researchers and clinicians in automatically generating a functional map from an SCS implant.

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Analysis of Muscle Activation Sequences in Vertical Jump

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Introduction: Vertical jump performance is a key indicator of athletic ability, particularly in sports that require explosive power. While increasing muscle strength is essential, optimizing muscle activation coordination and timing also plays a critical role in maximizing jump height. Computational models such as OpenSim and SCONE can predict muscle activation patterns that optimize performance, yet the extent to which proficient human jumpers follow these optimal patterns remains unclear. This study aims to compare real-world muscle activation patterns obtained through OpenSim with SCONE-generated optimal activation sequences. Additionally, we explore the potential application of these findings in Functional Electrical Stimulation (FES) strategies to enhance neuromuscular coordination.

Methods: Muscle activation sequences of a proficient jumper were analyzed using OpenSim's computed muscle control (CMC) method, which estimates muscle activations from measured kinematic data. These estimated activations were then compared to SCONE's optimization-based muscle activation patterns designed to maximize jump height. The comparison focused on identifying similarities and discrepancies in activation timing and magnitude across key muscle groups.

Results: SCONE's optimized activation sequences and OpenSim's computed muscle activations exhibited broad similarities in activation timing for key muscles, but notable differences in activation magnitude were observed. While the proficient jumper's muscle activation sequence largely followed the expected optimal activation order, certain muscles showed different activation intensities compared to the computationally predicted values. However, due to the inherent limitations of OpenSim's computed muscle control method, the lack of electromyographic (EMG) data remains a key limitation in validating these findings.

Discussion and Conclusion: This study provides a novel comparison between real-world and computationally optimized muscle activation patterns for vertical jumping. The results indicate that proficient jumpers exhibit activation sequences that approximate SCONE's optimized patterns, suggesting the potential for computational models to inform training strategies. Notably, the findings support the feasibility of using SCONE-predicted muscle activations in FES-based interventions to improve neuromuscular coordination. Future research will integrate EMG measurements to validate computational predictions and investigate the application of SCONE-driven FES strategies to enhance jump performance in less experienced individuals. This approach introduces a new paradigm in athletic training and rehabilitation, shifting focus from pure strength training to neuromuscular coordination optimization.

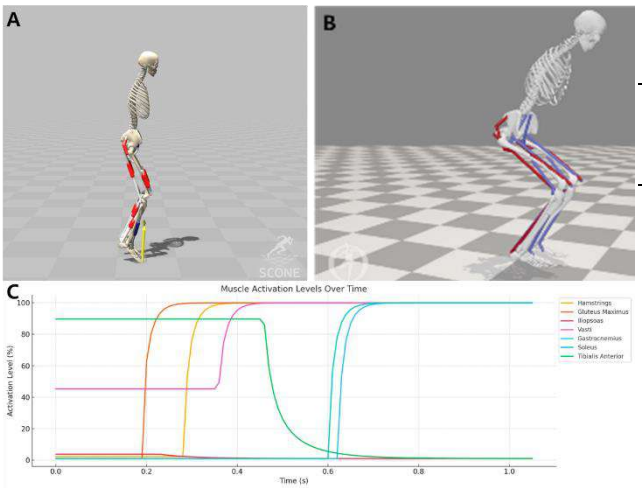


Figure **1**: (A) SCONE interface. (B) OpenSim interface. (C) Finalized muscle activation sequence plot showing key muscle timing.

Table 1: Activation and Deactivation Timing of Key Muscles During Vertical Jump.

Muscle	**Activation Timing (%) [Activation Level]**	**Deactivation Timing (%) [Activation Level]**
Hamstrings	36[99.0%]	-
Glut Max	27[99.0%]	-
Iliopsoas	0[3.7%]	35[1.5%]
Vasti	0[45%] → 37[99%]	-
Gastroc	70[99.0%]	-
Soleus	68[99.0%]	-
Tib Ant	0[89.7%]	76[1.5%]

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IMPROVEMENT IN MOTOR FUNCTIONS OF INCOMPLETE SPINAL CORD INJURED PATIENTS AFTER HYBRID FES CYCLING TRAINING

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Introduction: The benefits of FES-guided cycling therapy have been demonstrated in many studies, both for stroke and spinal cord injured patients. Traditional FES cycling therapy can be complemented with simultaneous voluntary arm cycling. This type of training is called hybrid FES cycling and is suggested to be more effective in rehabilitation of incomplete spinal cord injured (iSCI) patients than legs-only FES-assisted cycling [1]. Based on the outcome measures recorded during hybrid FES cycling training and during 10 meter walking tests, and in traditional clinical tests, we investigated how motor functions of iSCI patients with lower limb paresis improved with the training.

Methods: Five iSCI patients (P1-P5) were involved in this study. Their characteristics prior the hybrid FES cycling training are shown in Table 1. They had some ability to walk at least with assistive tools. They participated in a 12 weeks long hybrid FES cycling training program, 2 training sessions per week, 30 minutes per session. In each training session they performed FES assisted lower limb cycling and voluntary arm cycling simultaneously, using MotoMed Viva2 arm & leg cycle ergometers (Reck GMBH, Betzenweiler, Germany), equipped with multi-channel electrical stimulators to stimulate quadriceps and hamstrings muscles (pulse witdth 300μs, frequency: 30Hz, amplitude 20-50mA). We measured the average power output and the elapsed distance during the active cycling time. Before and after the training program, clinical assessments were taken, when we documented the used assistive tools, the ASIA, SCIM III and WISCI scores, and measured the walking speed during 10 meter walking tests.

Results: Four patients showed improvement in power output, in cycled distance and in clinical outcome measures. Patient P5 showed improvement only in clinical outcome measures. For three patients there was a change in assistive tools by the end of the training: P1 and P2 were able to walk without any assistive tool at the end of the training. P3 changed the 2 crutches to one. The scores in the SCIM III and WISCI scales increased appr. by 50% in the cases of two participants (P1, P2), at a less extent in one case, and didn't change in the others. The ASIA classification changed (C to D) in P1 and P2 at the end of the training. Regarding the distance covered during active cycling, Patient P3 cycled 38% longer distance after than before the training. This value was 29% for P4, and 13% for P5, while P1 and P2 did not show improvement in cycling distance. Each patient showed an improvement in average power output scores (Figure 1). The power output curves are not monotonically increasing, but the slopes of the trend lines show an increase (r^2=0.77, r^2=0.88, r^2=0.75, r^2=0.92, r^2=0.45 for P1, P2, P3, P4, P5 respectively). Regarding the assessments of walking abilities, the average speed during 10 meter walking, changed from pre- to post-training as follows: P1: from 0.65 to 0.74 m/s, P2: from 0.15 to 1.03 m/s, P3: from 0.57 to 0,72 m/s, P4: 0.9 to 1.36 m/s, P5: from 0.1 to 0.12 m/s. This improvement is smaller than what Zhou et al. 2018 reported, but they applied intense hybrid FES cycling training (5 times per week, 60 minutes) [1].

Table 1: Participant's characteristics before the training program

ID	Age (Year)	Level of Injury	Cause of injury	Initial supplementary devices	ASIA score
P1	70	L1	Surgery	rollator	C
P2	63	C2, T11-L3	Traumatic	walker, 1 (left) knee brace	C
P3	49	T9	Surgery	2 crutches	D
P4	46	C4-C8	Surgery	none	D
P5	40	C5	Traumatic	rolling trolley, 2 peroneus lifters, 2 knee braces	C

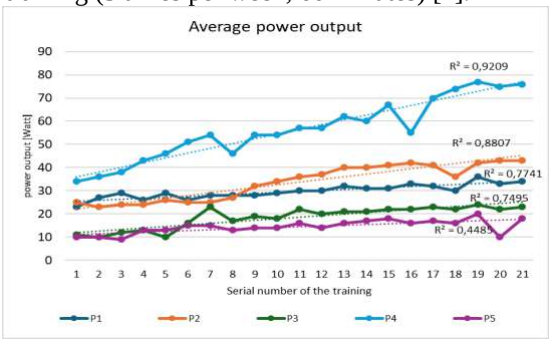


Figure 1: Average power output on the course of hybrid FES training sessions of 5 iSCI patients.

Discussion and conclusion: The improvement in the patients' cycling and walking performance after low intensity hybrid FES cycling training is reflected in the results of clinical outcomes, power output, cycling distance and walking speed. As other factors may also affect the rate of improvement, the progress that is attributed to hybrid FES cycling is an object of future studies. Although, our results suggest that even low intensity hybrid FES cycling training can foster improvements in the patients' motor functions.

Acknowledgement: The project was supported by the Ministry of Culture and Innovation from the National Research Development & Innovation Fund, Hungary, financed by the application program MEC_R 149078, and TKP2021-EGA35.

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Analysing the responses evoked by multi-contact epineural electrical stimulation to restore upper-limb functions in complete tetraplegia

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Introduction: Functional electrical stimulation (FES) is currently the only technology enabling functional restoration of grasping in individuals with tetraplegia when active muscle resources below elbows are insufficient for tendon or nerve transfer surgeries. Similar to the first implanted FES neuroprosthesis, Freehand™ (Neurocontrol, USA), most approaches directly stimulate individual sublesional muscles, using various electrode types (surface, intramuscular, or epimysial). These devices often require numerous internal components, with each muscle activated by a dedicated electrode [1]. Instead, we propose a neural stimulations solution with a single epineural multi-contact electrode targeting multiple muscles. This approach requires less energy, reduces the number of implanted components, and lowers the risk of complications such as infections, failures, and surgical risks due to less invasive procedures [2;3]. The challenge of such an approach is the lack of prior histological knowledge; indeed, the epineural electrode surrounds a nerve whose anatomical details are not known. The adjustment of configurations (combinations of active contacts) and stimulation parameters is done empirically based on the observation of induced movements. In this article, we propose to analyse evoked electromyographic signals measured on the surface of the forearm and compare them with the kinematics of hand movements reconstructed from multi-camera videos.

Methods: 2 participants with high tetraplegia (C4, AIS A) were included. The study was approved by the National Ethics Committee (ClinicalTrials.gov NCT05555914). The device consisted of 2 multi-contact epineural cuff electrodes (CorTec GmbH, Germany) composed of 2 external rings and a number of inner contacts adjusted to the diameter of the targeted nerve (8 for the median nerve and 6 for the radial nerve) each connected to individual percutaneous cables and an extracorporeal connector. 1 external multi-source current-controlled stimulator (STIMEP, INRIA, Montpellier) connected to a computer was used to deliver stimulation. Electrodes and cables were implanted during 28 days. Once a week, 12 wireless electrodes (Delsys, Natick, MA) were placed on the skin to record evoked electromyography (eEMG) induced by FES. eEMG data was processed offline using Matlab software. 4 webcams fixed on a frame facing participants, calibrated and running mediapipe allowed to estimate hand kinematics using a data fusion algorithm.

Results: The 2 participants were able to perform functional grasping tasks with various objects. Three main hand gestures were executed: hand opening, palmar grasp and key-grip. We analysed the eEMG and kinematic data together to formulate hypotheses about the muscles recruited by a set of predefined stimulation configurations - resulting from our previous modelling studies [4;5] - associated with the different types of grasps observed (palmar and keygrip).

Discussion and conclusion: This study presents promising preliminary results as part of a global effort to identify the muscles recruited by the different stimulation configurations in order to unveil the link between recruitment patterns and functional movements. In the future, musculoskeletal modelling will enable the development of an algorithm to extract this information in real time, providing clinicians a tool to help them optimally configure the neuroprosthesis

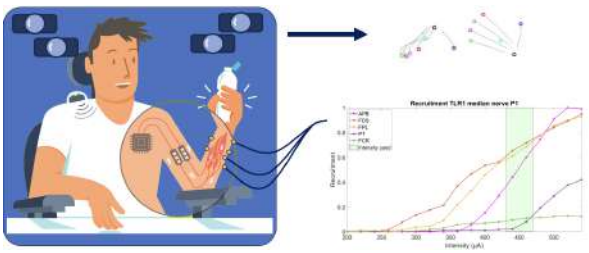


Figure 1: Schematic view of the setup

Funding: ISITE MUSE Univ Montpellier (AGILISTIM).

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REUSABLE TEXTILE ELECTRODES: A SCALABLE SOLUTION FOR LONG-TERM NEUROSTIMULATION APPLICATIONS

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Introduction: This study aimed to develop scalable, reusable, flexible, and breathable textile electrodes for neurostimulation applications. Neurostimulation technologies are an important group of interventions for pain relief, rehabilitation, and neuromuscular modulation [1–2]. Despite their clinical utility, traditional hydrogel electrodes limit long-term use due to skin sensitization and irritation [3]. To overcome these challenges, we developed textile-based electrodes that are washable, flexible, and breathable, while maintaining performance over extended use. This study aimed to evaluate the feasibility and performance of our reusable textile-based electrodes as a durable and comfortable alternative for long-term neurostimulation applications.

Methods: Textile electrodes were fabricated using a flat knitting machine with stainless steel (SS) conductive yarn. A 3D design ensured uniform skin contact and comfort. Electrode performance with water-based lotion was evaluated in 21 participants (11 males, 10 females; ages 26.3 ± 3.8 to 28.7 ± 4.5 years) using a PalmSens4 system for skin-electrode impedance and a DS8R stimulator for sensorimotor thresholds, including detection threshold (DT), motor threshold (MT), full movement threshold (FMT), just noticeable difference (JND), and Weber's Fraction [6]. Durability was assessed via cyclic washing (30 residential cycles) and stretch-loading tests (1000 cycles at 50% break strain). Usability was evaluated for up to six hours of wear to assess the consistency of performance of the developed electrodes with lotion applied to the skin. Quantitative and qualitative feedback was gathered to assess user comfort and perceived sensations during neurostimulation and was analyzed using statistical comparisons (two-way ANOVA) to assess differences in performance between textile and hydrogel electrodes across key metrics [4].

Results: The textile electrodes did not show statistically significant differences ($p > 0.05$) in performance to traditional hydrogel electrodes across key metrics (Tab. 1). Durability testing confirmed no statistically significant degradation in performance after 30 wash cycles or mechanical stretching. Notably, the electrodes maintained functional efficacy over six hours of wear (fig. 1), providing comfortable sensorimotor responses with no noticeable decline in stimulation quality. Users reported comparable comfort and sensation to those of conventional hydrogel electrodes.

Discussion and conclusion: This study presents a novel scalable textile-based approach to neurostimulation that addresses key barriers to long-term wearable use by combining durability, comfort, and efficacy. The results support integration into smart garments for broader clinical and personal applications

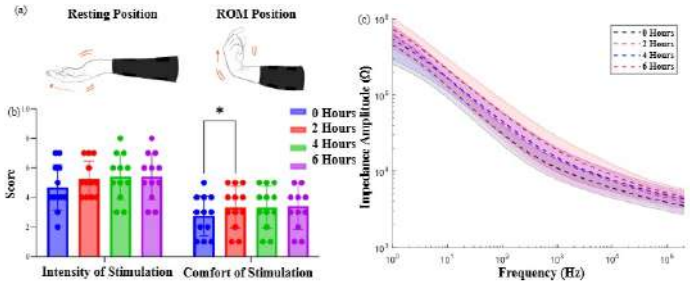


Figure **1**: (a) Illustration of evoked wrist flexion movements produced by stimulation, (b) Average scores for intensity and comfort level of the stimulation over 6 hours of wear, and (c) Average skin-electrode impedance of over 6 hours of wear.

Table 1: Functional Comparison of Hydrogel and Stainless Steel (SS) Textile Electrodes.

Metric	Hydrogel	Textile
Impedance - 5kHz (Ω)	602.9 ± 149.4	12544 ± 5237
DT (mA)	3.0 ± 0.9	2.7 ± 1.1
MT (mA)	9.3 ± 2.2	9.2 ± 1.7
FMT (mA)	12.1 ± 2.6	12.6 ± 1.7
JND (mA)	4.4 ± 1.1	4.2 ± 1.1
Weber's Fraction	0.52 ± 0.28	0.68 ± 0.43
Stimulation Intensity	4.3 ± 1.6	5.2 ± 1.3
Stimulation Comfort	2.5 ± 1.6	3.2 ± 1.5
Wash Cycle Durability	N/A	30+ Cycles
StretchDurability	N/A	1000+ Cycles

Acknowledgments: Authors acknowledge MyantX Inc. (Canada) for financial support of this research.

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The Cleveland Open Source Modular Implant Innovators Community (COSMIIC)

The overall goal of the Cleveland Open Source Modular Implant Innovators Community (COSMIIC) is to establish an open source, modular network of active implantable devices for use in pre-clinical and early feasibility human research, and to provide ongoing support for this technology through a vibrant, sustainable community of users. The concept is based on our established platform ecosystem, the Networked Neuroprosthesis (NNP), which provides a solid technological platform with an established regulatory status for human use. The COSMIIC concept is being established through major funding from the National Institutes of Health (NIH) Stimulating Peripheral Activity to Relieve Conditions (SPARC) Program. The project includes a broad investigative team in Cleveland, OH, USA at Case Western Reserve University (CWRU), MetroHealth System (MHS), Veterans Affairs Northeast Ohio Healthcare System, and the Cleveland Clinic Lerner College of Medicine; as well as investigators at the University of Michigan and the University of California, Los Angeles (UCLA).

The "COSMIIC System" is based on the platform NNP System, which was developed at Case Western Reserve University. The NNP platform is a system of interoperable and integrated modules that can simultaneously electrically activate, block, and sense throughout the body. The system can record and process electroneurogram (ENG), electromyogram (EMG), intracortical signals, electrocardiogram (EKG), kinematic variables, and temperature. Each module can directly communicate with all other modules through an established network communication protocol. The system can process signals to implement complex closed-loop control without requiring non-implanted hardware. All modules can be intermixed, with multiple modules of any type incorporated into a functioning network with the desired features. This platform is designed to allow future innovation by the community of users, with an openly expandable network that could incorporate the addition of new modules, including chemical sensors, optics (sense and drive), ultrasound, etc. Importantly, the existing NNP platform components (power module, stimulator module, biopotential recording module, network cable, electrodes) already have Investigational Device Exemption (IDE) approval from the US Food and Drug Administration (FDA) and have been successfully implanted and implemented in human research participants. Thus, the COSMIIC System has the necessary features to provide the modular platform ecosystem for use by the bioelectronic community for the foreseeable future. We will enhance the modular NNP System with additional functionality with includes: electrical nerve conduction block, high density electrode arrays, and remote powered sensors; along with a wearable wireless link to allow seamless integration of external sensors and actuators for research purposes. These deliverables are expected to substantially broaden the tools available for human research in bioelectronics, neuromodulation, and neuroprosthetics.

We expect that an open source modular active implantable system will provide several advantages to the research community across the entire spectrum, from basic physiological studies to human application. Specifically:

1) Previous attempts at creating a "universal" implantable device have fallen short because it is not possible to create a single centralized device that anticipates the innovations of the future. A modular approach, such as the NNP System, is required, in which the ecosystem allows freedom for innovation of new features without requiring modification of the entire platform.
2) The NNP Platform provides extensive sensor networks and datalogging that would be difficult to justify incorporating into a purpose-built implant system due to cost constraints. These built-in capabilities provide the opportunity for rich data collection regarding a variety of physiological variables.
3) The NNP System is a fully implanted system, capable of internal powering, processing, and closed-loop control without requiring external components (except for battery recharge). This is very important for the bioelectronics community because the intimate control of the peripheral nervous system required by many clinical applications necessitate at least some, or all, of the activation and sensing be performed through implanted components. The system is capable of interfacing with external components as needed.
4) The NNP Platform has already demonstrated translation through the regulatory hurdles and into human early feasibility study. This reduces the major disincentive for the translation of ideas to human use.
5) Designed as a real-time closed-loop neuroprosthetic system, which is directly applicable in bioelectronics.

The goal of the COSMIIC project is to develop an assemblage of modular interoperable implantable components with advanced features, and then freely license this technology to the world without any limits imposed on its future use, modification, dissemination, or commercialization. The goal of COSMIIC is to systematically remove or reduce each of the barriers to the introduction of implantable devices for human use to the maximum extent possible.

Enhancing Neural Interfacing with the Peripheral Nervous System: Stability, Selectivity and Information Content

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Abstract: *The integration of advanced nerve interface technology is crucial for improving chronic neural recordings from the peripheral nervous system. This study presents the capabilities of nano wires (nWs) made from carbon nanotube yarn (CNTY) electrodes, which exhibit low flexural rigidity and compact size, enabling reliable long-term selective recordings from multiple fascicles of nerves. We evaluate the chronic recording capabilities of nWs electrodes implanted in individual fascicles of the sciatic nerve in rats, achieving signal-to-noise ratios (SNR) between 13 -18 dB and demonstrating consistent information of 4bits/fascicles retrieval over 12 weeks. Additionally, we validate a novel recording technique by implanting nWs electrodes in the median nerve of a pig, effectively interfacing with seven fascicles and recording responses to sensory stimuli such as proprioception and nociception. This research highlights the advancement of nWs technology in overcoming limitations of current neural interfaces, offering new possibilities for neural rehabilitation and control by enabling simultaneous chronic recordings from a higher number of fascicles.*

Keywords: Peripheral Nerve Interfaces, ENG, Signal to Noise Ratio, Mutual Information, Shannon Entropy, Carbon

1. Introduction: Despite the advanced prosthetic devices available, individuals with traumatic amputations face challenges in fully restoring limb functionality, which negatively impacts their quality of life. The main hurdle in prosthetic device development lies in the absence of a comprehensive control signal capable of providing the necessary degrees of freedom. Although these neural signals exist within the nerves, their recording proves difficult. Recent devopments at the Neural Engineering Center of Cleveland have focussed on the carbon naonowires (nWs), made of small diameter (10-20um) carbon nanotubes yarn. These nWs have very low flexural rigidity similar to that or nerves making then highy suitale for long-term implant (Kotamraju et al. 2024].

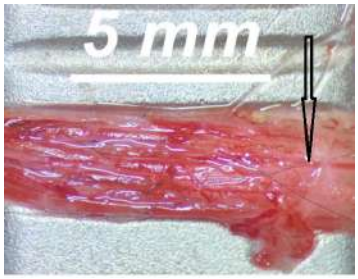


Fig1: Carbon nanowires, 10um in diameter, inserted in seven fascicles of the pig's median nerve (arrow indicates one such nnowire)

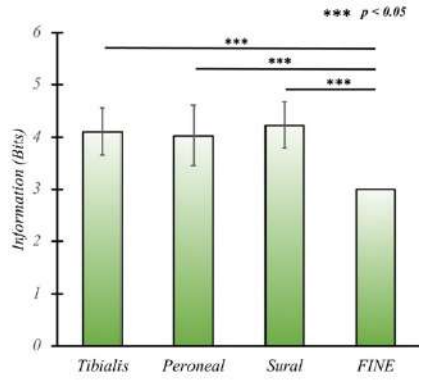


Fig 2: Information content nanowires inserted in three fascicles. Each recording carries about 4bits of information. The information content was stable over 4 month- period. That number of bits is higher than that recovered from a whole sciatic nerve in dogs with a FINE.

2: Methods: nWs flexibility requires implantation with either a carrier tungsten electrode or with a suture and needle attached to the Nw. Many such nWs can be implanted in several of the fascicles of nerves (See fig 1).

3: Results: The SNR and information content was quantified over a period of 4-month in the 3 fascicles of the sciatic nerve of rats. All the electrodes demonstrated a mean SNR with a range between 13 and 18 dB across six rats and was stable over a period of 12 weeks. Four bits of information were recovered in each fascicles (Fig2) and this number is higher than that obtained in mongrel dog sciatic nerve with the Flattening Interface electrode (FINE) [Eggers et al, 2017]. Mutual information analysis revealed that 1.4 bits on average are shared between two fascicles. Acute experiments in pigs showed that nWs implanted in seven fascicles could provide selective fascicular activation in response to applied sensory stimuli. Tactile and proprioception stimuli yielded highly selective neural response.

4: Significance: While the nW electrodes only have one contact per electrode, the ability to implant these electrodes in each fascicle of the human nerve would yield ~20 to 30 individual channels providing a total of 52 to 78 bits (20*2.6 bits) of independent information encoded in the spiking activity. Moreover, they are highly stable in chronic preparation and provide selective recording making this technology an excellent candidate for recovering motor intent and controlling motor prostheses

6. Acknowledgement: This work was funded by the National Institutes of Health (5R01NS032845-23). The authors would like to express their gratitude to William Marcus who helped monitor animals during the surgery and recovery.

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SMART GARMENT FOR AUTOMATIC ASSESSMENT OF ELECTROMYOGRAPHY DURING FES

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Introduction: Automatic and seamless acquisition of electromyograms (EMG) during FES remains desirable for both clinical and research applications. Acquiring EMG could: (i) provide continuous monitoring of coordinated volitional muscle activity as a biomarker of recovery, (ii) assess muscle fatigue, (iii) facilitate the implementation of EMG-controlled stimulation, and (iv) enable the integration of computational models to predict adaptation of musculoskeletal tissues [1, 2]. Yet, integrating EMG acquisition with commercial FES systems remains challenging. Using separate equipment often leads to complex setups that hinder movement, increase donning time, and introduce stimulation artefacts into EMG signals. To overcome these limitations, we developed the Smart BioWrap (Fig. 1a), a personalised garment designed to rapidly apply FES electrodes while incorporating EMG sensors and electronics for signal processing. In this proof-of-concept study, we demonstrated the feasibility of acquiring EMG data while delivering FES using the Smart BioWrap.
Methods: The Smart BioWrap is a neoprene-based wearable device compatible with commercial FES systems. It integrates a custom-developed wireless EMG acquisition board (2000 Hz sampling, 24-bit ADC, SNR 22 dB, CMRR >60 dB) to record muscle activity from agonist-antagonist pairs in real time. Quadriceps stimulation (RehaStim2, HASOMED) was delivered at 25 Hz with a 500 µs pulse width, while EMG signals were recorded from the femoris muscle of one participant under isometric conditions (ethics approval #GU2022/664). Stimulation amplitude was increased from 5 mA to 30 mA in 5 mA steps, with each pulse lasting 0.5 seconds followed by a 0.5 second rest. Stimulation artefacts were removed using software blanking, after which raw EMG were band-passed (10–300 Hz) and notch filtered (50 Hz) using 3rd-order Butterworth filters. An adaptive filter was used to extract voluntary EMG and M-wave [3]. M-wave were qualitatively analysed to evaluate the ability of the system to capture neuromuscular responses to stimulation.
Results: The recorded EMG revealed the presence of electrical stimulation artefacts, M-wave, and volitional EMG component. Analysis of EMG data across varying stimulation currents showed a consistent increase in M-wave amplitude with higher current intensities (Fig. 1b). The volitional component of the EMG could be successfully isolated from the the raw EMG signals containing both stimulation artefacts and M-waves (Fig. 1c).
Discussion and conclusion: We designed and developed Smart BioWrap, a garment compatible with existing FES systems, to enable rapid acquisition of EMG during rehabilitation. In this first proof-of-concept study we verified the ability of the system to acquire high quality EMG data during electrical stimulation. The industrial design of the garment was developed through a co-design framework, integrating user considerations, and received positive feedback for its comfort and ease of use by both patients and clinicians. Future work will extend the use of Smart BioWrap to all major muscle groups in the lower limbs to continuously acquire EMG during FES cycling. Overall, enabling rapid single wearable devices that can be retrofitted to existing commercial FES systems could support improving rehabilitation strategies through continuous monitoring of recovery and integration with computational models [2].

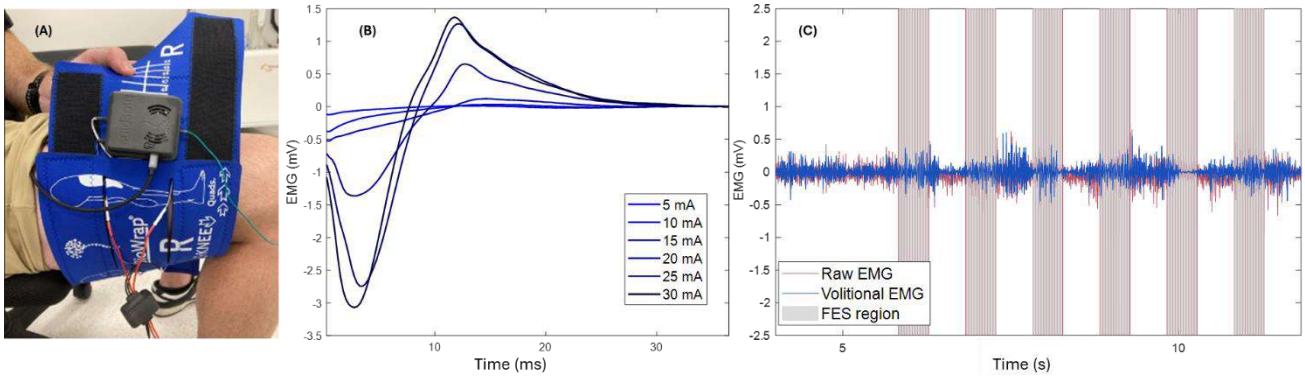


Figure **1**: (a) Smart BioWrap containing the EMG acquisition unit; (b) M-wave at increasing current values; (c) volitional and raw EMG with the shaded regions corresponding to the stimulation being delivered.

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rTMS for Sleep Therapy Promotes upper-limb Motor Function Recovery After Stroke by Improving the Off-Line Consolidation of Motor Learning

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Introduction: Current rehabilitation strategies for post-stroke hemiplegia primarily emphasize skill acquisition through repetitive training. Motor memory consolidation is essential for enhancing the efficacy of repetitive training, while sleep-dependent memory consolidation play a crucial role in improving motor learning[1]. However, sleep disorders are also common among stroke patients and can significantly hinder motor skill acquisition. Therefore, treating sleep disorders in stroke patients may enhance motor learning and facilitate motor function recovery. This study aims to apply repetitive transcranial magnetic stimulation (rTMS) to the treatment of sleep disorders in stroke patients, explore its effects on sleep quality and motor function, and evaluate motor learning ability, confirming that rTMS treatment for sleep disorders can improve upper limb motor function recovery after stroke by promoting motor learning ability.

Methods: A total of 21 hospitalized stroke patients with hemiplegia and sleep disorders were recruited and randomly assigned to either an intervention group or the control group. The control group received regular rehabilitation therapy, including physiotherapy, rTMS intervention targeting the primary motor cortex (M1), and manual therapy. The intervention group received the same rehabilitation therapy as the control group, with an additional 10 sessions of low-frequency (1 Hz) rTMS targeting the right dorsolateral prefrontal cortex (DLPFC) for 20 minutes per session[2], five times a week. Sleep quality was evaluated using the Pittsburgh Sleep Quality Index (PSQI) and actigraphy, motor function was assessed with the upper limb Fugl-Meyer Assessment (FMA), and motor learning ability was measured using the Finger Tapping Sequence Learning (FTSL) task, both pre- and post-intervention. A two-way ANOVA was conducted to compare pre- and post-intervention outcomes between the groups, and Pearson correlation analysis was performed to explore the relationship between changes in sleep quality and motor function.

Results: The rTMS intervention group showed a significant reduction reduced in PSQI scores compared to the control group ($F(1, 19) = 26.55$, $P < 0.0001$). Actigraphy parameters indicated improved sleep efficiency ($F(1, 19) = 5.894$, $P = 0.0253$), increased total sleep time ($F(1, 19) = 21.46$, $P = 0.0002$), and reduced wake time after sleep onset ($F(1, 19) = 16.27$, $P = 0.0007$). Furthermore, the Δupper limb FMA scores showed significant improvements in the intervention group ($P= 0.0005$). Correlation analysis revealed a negative association between the decrease in PSQI scores and improvements in FMA scores within the intervention group ($r=-0.8542$, $P=0.0008$). Additionally, the FTSL task demonstrated significant improvements in accuracy ($F(1, 20) = 8.555$, $P = 0.0084$) and reaction time ($F(1, 19) = 5.067$, $P = 0.0364$) in the intervention group compared to the control group.

Discussion and conclusion: These findings suggest that rTMS interventions targeting sleep disorders in stroke patients can effectively promote upper limb motor recovery by improving motor learning ability through enhanced sleep-dependent memory consolidation.

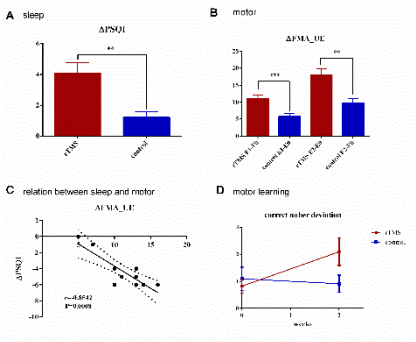


Fig 1. The result of sleep, motor, and motor learning between two groups before and after the intervention

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TEMPORAL SUMMATION IN HUMAN PERIPHERAL AXONS WHEN STIMULATED TRANSCUTANEOUSLY WITH A 10-KILOHERTZ-FREQUENCY WAVEFORM

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Introduction: Transcutaneous spinal cord stimulation, as used for rehabilitation of impaired motor function after spinal cord injury, often involves a 10-kHz waveform modulated to produce short, repetitive bursts of stimulation. It is thought that the kilohertz-frequency waveform facilitates the summation of subthreshold depolarisations, but the optimal burst duration for nerve stimulation has not been systematically investigated. The aim of this study was to determine the effect of the number of pulses per burst of stimulation for a 10-kHz waveform on the activation of sensory and motor axons in the ulnar nerve.

Methods: In eleven healthy abled-bodied adults, the left ulnar nerve was stimulated transcutaneously with single bursts of a 10-kHz waveform that contained 1, 2, 4, 6, 8, or 10 biphasic pulses (Fig. 1), in random order. The left hand was held in a splint to prevent flexion of the wrist during stimulation. Compound muscle action potentials (CMAPs) from the abductor digiti minimi muscle were measured from motor threshold up to the maximal CMAP (M_{max}). Stimulus intensities were expressed in terms of both current amplitude and total phase charge because the number of pulses alters the total charge at a given current amplitude. The efficacy of each waveform was determined at M_{max} as CMAP amplitude divided by total phase charge. Sensory nerve action potentials (SNAPs), measured antidromically from ring electrodes placed around the fifth digit, were recorded simultaneously with CMAPs at each stimulus intensity.

Results: For CMAPs and SNAPs, the increase in number of pulses shifted the stimulus-response curves to the left when stimulus intensity was expressed as current amplitude. Therefore, less current was required to activate sensory and motor axons. The current amplitude at motor threshold decreased as the number of pulses increased from one up to six pulses, and at M_{max}, current amplitude decreases from one up to four pulses. Conversely, the increase in number of pulses shifted the CMAP and SNAP stimulus-response curves to the right when stimulus intensity was expressed as total charge. At motor threshold, the total charge increased with the number of pulses from one up to the maximum of ten pulses. At M_{max}, the total charge increased from two up to the maximum of ten pulses. Efficacy at M_{max} decreased as the number of pulses increased from one up to six pulses.

Discussion and conclusion: These findings provide evidence that subthreshold depolarisations at 10 kHz summate in large diameter sensory and motor axons in humans. The optimal number of pulses for summation remains unclear. Although less current is required at threshold when the number of pulses increases, the total charge increases, resulting in decreased efficacy. However, more than six pulses is suboptimal for summation, as the decrease in threshold current plateaued after six pulses while total charge continued to increase.

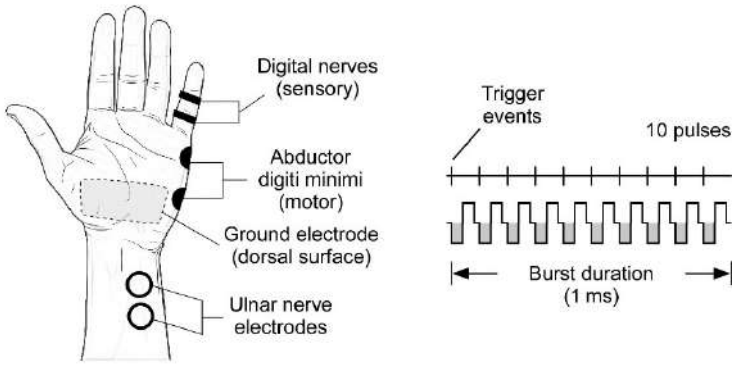


Figure **1**: Experimental setup and stimulus parameters.

Efficacy and Mechanism of Cerebellar iTBS in Promoting Upper Limb Motor Recovery After Stroke

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Key word: Stroke rehabilitation, Intermittent theta burst stimulation, Upper limb motor recovery

Background: The cerebellum plays a crucial role in motor recovery after stroke, yet its specific contributions have received limited attention in research. Intermittent theta burst stimulation (iTBS), an important pattern of transcranial magnetic stimulation (TMS), has been proved to effectively induce neuroplasticity. However, whether cerebellar iTBS can enhance upper limb motor recovery after stroke and the underlying mechanisms remain unclear.
Objective: This study aims to evaluate the efficacy and neural mechanisms of cerebellar iTBS on upper limb motor function recovery in stroke patients using multimodal assessments.
Methods: A randomized controlled clinical trial (RCT) was used in this study. 26 stroke patients were randomly assigned to either the cerebellar iTBS group (n=14) or the sham stimulation group (n=12). iTBS was applied to the cerebellar hemisphere ipsilateral to the paretic limb, five times per week for two weeks (10 sessions in total). Stimulation parameters are as follows: intensity 80% of active movement threshold (AMT), intra-cluster frequency 50 Hz, inter-cluster frequency 5 Hz, total number of stimuli 600, total stimulation time 200 s. All patients also received standard pharmacological and conventional rehabilitation treatments. Clinical scales were used to assess upper limb motor function before, during, and after the intervention. Cortical excitability was measured using TMS, and resting-state and task-based fNIRS were used to evaluate functional connectivity and activation in regions of interest (ROIs). Data for this study were analyzed using IBM SPSS Statistics 27.0. For statistical analysis of outcome indicators, if data followed a normal distribution, a chi-square test or t-test was used depending on whether the variables were categorical or continuous. If data were normally distributed, a two-way repeated measures ANOVA was performed to evaluate the main effects and interactions between the "between-group factor". For non-normally distributed data, within-group and between-group differences were assessed using the Wilcoxon rank-sum test and Mann-Whitney U test, respectively.
Results: After the intervention, the cerebellar iTBS group showed significantly greater improvements in the Fugl-Meyer upper limb assessment ($P<0.05$) and the modified Ashworth scale ($P<0.05$) compared to the control group. No significant differences were observed between the groups in the modified Barthel index or the upper limb action

research arm test (P>0.05). Compared to baseline, the iTBS group showed a significant decrease in resting motor threshold in the intact M1 area (P<0.01) and increased activation in the affected BA4 area (P<0.05) as assessed by fNIRS. Functional connectivity between the affected BA4 and intact BA6, as well as between bilateral BA6 regions, also increased (P<0.05). Compared to the sham group, the iTBS group demonstrated stronger functional connectivity between the affected and intact BA6 regions (P<0.05).

Conclusion: Cerebellar iTBS significantly promotes upper limb motor function and reduces abnormal muscle tone in stroke patients. Changes in cortical activation and functional connectivity in BA4 and BA6 regions may underlie the observed therapeutic effects of cerebellar iTBS.

Development, Acute Placement and Muscle Recruitment of a Novel Interfascicular Electrode for Peripheral Nerve Stimulation

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Introduction: Peripheral nerve stimulation (PNS) has been implemented for various clinical applications including the alleviation of chronic neuropathic pain, sensory restoration following amputation and a wide range of autonomic therapies. The therapeutic benefit of peripheral nerve interfaces relies on the selectivity of the interface, which refers to its capability to activate specific axonal populations while avoiding activation of others. However, there is a trade-off between selectivity and invasiveness [1]. Invasiveness refers to the extent of physical interaction between the interface and the axonal population, which is characterized by the protective nerve membranes that are interrupted, namely the perineurium. We hypothesize that peripheral nerve electrodes that are placed between the fascicles -interfascicularly - may balance this trade-off of invasiveness and selectivity by allowing access to central axon populations while leaving the perineurium intact. Here we outline and characterize the development, placement and muscle recruitment of multi-contact interfascicular electrode placement into porcine peripheral nerves.
Methods: Inserter development allows the placement of multiple microwire interfascicular contacts to be acutely implanted into the median or ulnar nerves of N=7 anesthetized pigs through a small incision. A diagram of the position of the interfascicular microwire array is displayed in Figure 1. Electromyography (EMG) signals were recorded from downstream muscles via needle electrodes in response to stimulation of each interfascicular contact to quantify the recruitment behaviour of the interfascicular electrodes. The nerve was then excised, and micro-computed tomography was performed to visualize the relative positions of the microwires and fascicles.
Results: Muscle Recruitment: Multiple muscles across the implants were able to be independently recruited using interfascicular electrical stimulation, as defined by their recruitment curves. Additionally, similar or higher levels of muscle activation were observed with interfascicular electrical stimulation as compared to whole nerve extraneural stimulation suggesting functional feasibility. Placement: Across the total of N=30 placements, 24 (80%) of them appeared interfascicular as shown on the micro-computed tomography, while the remaining 7 (20%) were found to be intra-fascicular. Analysis of each nerve showed that interfascicular electrodes are well-distributed throughout the cross-sectional area of the nerve and can be placed centrally.
Discussion and conclusion: These results demonstrate that interfascicular electrode placement is a feasible and promising approach for placing a multiple, distributed contacts while preserving the perineurium and offering a potential balance between invasiveness and selectivity for peripheral nerve interfaces

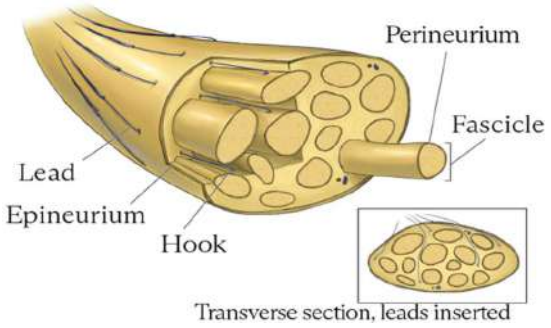


Figure **1**: Novel interfascicular interface for peripheral nerve stimulation.

Acknowledgments: Special thanks to FNI lab members, and the Animal Resource Center veterinary staff
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THE INTRACORTICAL VISUAL PROTHESIS PROJECT (ICVP): CLINICAL TRIAL STATUS AND RESULTS

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Introduction: The Illinois Institute of Technology is leading an 8-institution team for the clinical trial evaluation of the Intracortical Visual Prosthesis (ICVP). The ICVP project is funded by the NIH BRAIN Initiative (NIH award 5UH3NS095557-04) and aims to assess the feasibility of using the ICVP system, implanted in the occipital lobe, to produce artificial vision in up to five volunteers, for people with bare, or no, light perception.

Methods: The ICVP system is comprised of a group of implantable modules known as Wireless Floating Microelectrode Arrays (WFMA) - see Fig 1. WFMAs are implanted in the dorso-lateral area of the occipital lobe. WFMAs receive power and communications via a transcutaneous inductive link. Each WFMA, and each of its 16 intracortical AIROF electrodes, are wirelessly addressable to control the intracortical stimulation. Image information captured by a camera is translated to wireless WFMA commands which create phosphenes and other visual perceptions. The trial is exploring how the phosphenes might be combined to create a crude type of artificial vision. Two study participants have been implanted (Feb 2022 – 25 WFMAs, 400 electrodes (P1); Oct 2024 – 32 WFMAs, 512 electrodes (P2)). Electrodes' electrical characteristics (P1, P2), thresholds (P1, P2) and perceptions (P1), mapping (P1), and a camera interface for visually-guided tasks (P1), have been studied. P1 & P2 testing is on-going.

Results: 56 WFMAs (P1, P2) have demonstrated reliable functionality, for both stimulation control and reverse telemetry. One WMFA (P1) lost communication after 21 months: suspected due to damage during surgery. Over the first 6-26 months (P1), connection was lost to only two electrodes (suspected known issue). To-date, voltage transients for 382 electrodes show high-consistency and stable parameters of access resistance (Avg 54k), and polarization (Avg -0.3V). Early electrical testing in P2 shows a similar trend. Most perceptual thresholds (P1) have been stable (~+/-33%). Mapping (19 WFMAs in P1), combined with a head-mounted camera (visible and IR), and head scanning, was used to assess P1's ability for object and people localization [1]/recognition of large-scale shapes/letters, with encouragingly high (~70%) success. One expected visual seizure adverse event occurred for P1.

Discussion and conclusion: The WFMAs are designed for chronic implantation, in contrast to other studies [2]. For P1, new methods of pattern stimulation that enhance visual feature resolution (via gratings) were discovered in August 2024, improving grating acuity to 2.4cycles/degree: approximately a factor of 16 improvement from prior values, and validating our hypothesis for the need of a chronic interface to explore visual functionality. The implanted WFMAs have shown high technical stability, allowing for testing over an extended time period, facilitating the testing of a broad range of stimulation strategies. While the current limitation in electrode count does not allow for form vision, the ICVP system has been found to have useful sensory benefit as a supplement to other conventional visual rehabilitation aids.

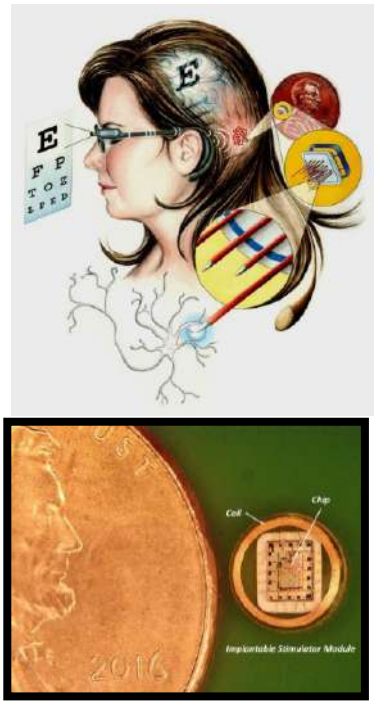


Figure **1**: The ICVP system concept (top); implantable WFMA module (bottom)

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Non-Invasive Brain-Controlled Spinal Stimulation for Enhancing Neuromotor Recovery in Incomplete Spinal Cord Injury

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Introduction: Transcutaneous spinal cord stimulation (TSCS) has emerged as a promising intervention for enhancing motor function in individuals with spinal cord injury (SCI) [1]. By combining TSCS with brain-computer interface (BCI) technology, its efficacy can potentially be amplified through the alignment of spinal activation with motor intention. This study aimed to evaluate the impact of a novel BCI-TSCS intervention on lower-limb motor function and corticospinal excitability in individuals with chronic incomplete SCI.

Methods: The study involved two intervention conditions, performed on separate days: (1) BCI-TSCS: TSCS was applied for 5 seconds when the BCI detected brain signals related to motor imagery of ankle dorsiflexion. (2) Random TSCS: TSCS was delivered in 5-second bursts at random intervals while participants remained at rest without engaging in motor imagery. Each sessions lasted 30 minutes, during which TSCS was delivered at a frequency of 30 Hz, targeting dorsal root sensory fibers. The stimulation site was between the T12 and L3 vertebrae regions showing the strongest spinal reflex responses in the tibialis anterior (TA) muscle. Stimulation intensity was adjusted to the motor threshold, defined as the lowest intensity required to elicit visible spinal reflexes. In the BCI-TSCS condition, electroencephalography (EEG) was used in real-time to detect cortical activity patterns corresponding to motor imagery, enabling precise synchronization of TSCS with these signals. The intervention's effects were evaluated by measuring motor-evoked potentials (MEPs) in the TA muscle using transcranial magnetic stimulation (TMS) to assess corticospinal excitability. Lower-limb motor performance was tested with a coordination task to assess functional improvements.

Results: The BCI-TSCS intervention led to a significant increase in corticospinal excitability, as evidenced by larger MEP amplitudes in the TA muscle immediately post-session ($p<0.05$). In contrast, no changes in corticospinal excitability were observed following the Random TSCS condition. Motor performance improvements were also observed after the BCI-TSCS intervention, with participants demonstrating enhanced coordination during the functional task ($p<0.05$). These outcomes suggest that synchronizing TSCS with cortical activity during motor imagery can strengthen the neural pathways between the brain and spinal cord.

Discussion and conclusion: This study demonstrates the efficacy of integrating BCI technology with TSCS to enhance both neural and motor outcomes in individuals with chronic incomplete SCI. Synchronizing TSCS delivery with cortical activity during motor imagery appears to reinforce the connection between brain signals and spinal circuits. The observed short-term enhancements in corticospinal excitability and motor performance underline the potential of BCI-TSCS as a rehabilitation strategy for SCI. This approach highlights the importance of integrating motor intention into neuromodulatory interventions to maximize therapeutic benefits. Future research should explore the long-term effects and optimize protocols to further refine this promising neuromodulatory therapy, which represents a significant step forward in advancing SCI rehabilitation and supporting motor recovery.

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PREDICTING MUSCLE RESPONSE TO FES THERAPY USING SURFACE EMG IN INDIVIDUALS WITH CERVICAL SCI

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Introduction: Cervical spinal cord injury (SCI) severely impairs upper extremity (UE) functions and limits independence and quality of life. Restoring UE function is a top priority for individuals with cervical SCI. Functional electrical stimulation (FES) therapy facilitates *functionally* useful movements and emphasizes volitional movement attempts from the patients. It has demonstrated promising results in improving UE function. However, inconsistent muscle response and variability in patient outcomes highlight the need for predictive methods to identify responder and non-responder muscles. To date, no predictive models exist to assess muscle responsiveness to FES therapy. This study aimed to predict muscle response using baseline surface electromyography (sEMG) signals and clinical variable, to optimize treatment plans and resource allocation, ultimately improving patient outcomes. Figure 1 provides a conceptual overview.
Methods: Seventeen participants with cervical SCI were recruited. Target UE muscles were identified by treating therapists before starting FES therapy. Baseline sEMG signals were recorded from the target muscles during voluntary contractions. Time- and frequency-domain features were extracted. Responder muscles were defined by a significant ($\alpha = 0.01$) positive Kendall's tau rank correlation between manual muscle testing scores (collected each session) and session numbers. We explored classifiers including support vector machines, k-nearest neighbors, random forest, and logistic regression, with leave-one-participant-out cross validation. Models were trained on (1) sEMG features, using standard features from myoelectric pattern recognition, (2) clinical variables, and (3) combinations of both. Evaluation metrics included Matthews correlation coefficient (MCC), F1 score, accuracy, precision, recall, and specificity.
Results: The final dataset consisted of clinical variables and sEMG recordings of 132 muscles from 17 participants; 43% were responders. A Random Forest classifier on forward-selected sEMG features (slope sign change, mean and median frequency, and second-order moment) yielded the best performance: MCC = 0.41, macro F1 score = 0.68, weighted F1 score = 0.74, accuracy = 0.76, precision = 0.72, recall = 0.42, and specificity = 0.92. Classifiers trained on this sEMG feature set consistently outperformed those using only clinical variables or combined features. Although adding AIS as a feature did not improve accuracy when using the entire dataset, training separate models based on motor completeness (AIS A-B vs. C-D) further boosted classifier performance.
Discussion and conclusion: This work highlights the potential of baseline sEMG signals for predicting strength recovery from FES therapy after cervical SCI. While trained on a small and unbalanced dataset, the models demonstrated promising results, suggesting opportunities for optimization with larger datasets. This work contributes to advancing the personalization and efficacy of FES therapy, ultimately improving quality of life for individuals with SCI.

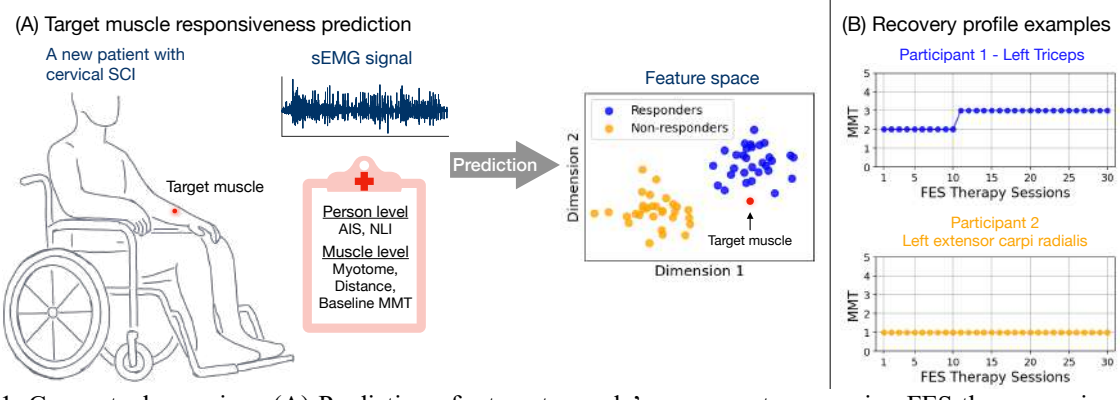


Figure 1. Conceptual overview. (A) Prediction of a target muscle's response to upcoming FES therapy, using features extracted from sEMG signals and clinical variables. The feature space is synthetic for demonstration purposes. (B) Recovery profile examples of FES therapy from two muscles after 30 sessions of FES therapy.

CHRONIC EVALUATION OF A WIRELESS INTRASPINAL INTERFACE FOR MOTOR FUNCTION RECOVERY IN THE PORCINE MODEL

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Introduction: Spinal cord injury (SCI) causes severe motor and sensory deficits [1]. Intraspinal microstimulation (ISMS) offers potential for restoring motor function post-SCI, with long-term functionality shown in small animal models [2, 3]. However, long-term functionality in larger models remains unexplored. Challenges with existing ISMS concepts include possible lead fracture, CSF leakage, tethering-induced tissue damage, and neuronal damage due to repeated insertions. To address these challenges, a wireless ISMS interface was previously evaluated in a large animal acute experiment [4]. In this study, a dual-chip Wireless Floating Microelectrode Array (WFMA) was chronically implanted in pigs to evaluate surgical feasibility, electrochemical performance, and functional stability.

Methods: Seven in-vivo experiments were conducted on adult spinally intact pigs (50 kg). Experiments 1–5 revealed that the laminectomy procedure itself results in functional deficits, prompting surgical refinements such as duroplasty graft to reduce mechanical pressure, hemostatic agent to prevent epidural hematoma, dural graft matrix for CSF containment, and a modified epidural extension cord for spinal protection (shown in Fig. 1A). In experiments 6 and 7, the dual-chip WFMA device was implanted for 70 and 22 days, respectively (the dual-chip device is shown in Figs. 1B and 1C). Functional recovery was measured via the porcine thoracic injury behavioral scale (PTIBS), electrochemical performance by voltage transients, functional stability by stimulation thresholds, and tissue integrity via histological evaluation.

Results: Incorporating surgical modifications led to significant functional recovery improvements in experiments 6 and 7, with PTIBS scores of 9 and 7, respectively. The animal in experiment 7 showed potential for further recovery had the study duration been extended. Both animals maintained intact sensory pathways and exhibited balanced, weight-bearing ambulation. Voltage transient measurements indicated acceptable electrochemical performance, and stimulation thresholds remained within previously reported upper current limits for ISMS [2,3]. Histological evaluation showed preserved spinal cord cross-sectional curvature, attributed to duroplasty reducing dual-chip device-induced mechanical pressure.

Discussion and conclusion: This study demonstrates the functional stability of a wireless ISMS system, for the first time, in a large animal model. Refinements in surgical techniques enabled significant recovery and established a mature large animal model for future ISMS testing.

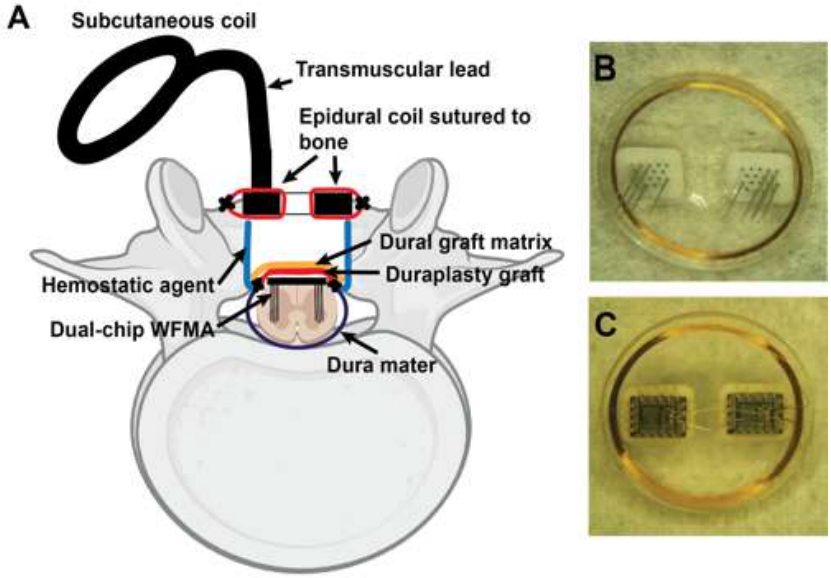


Figure 1: The implantation procedure (A). Top view of the dual-chip WFMA (B). Bottom view of the dual-chip WFMA (C).

Acknowledgments: We would like to acknowledge the University of Chicago's Animal Resource Center (ARC), as well as Dr. Vivian Mushahwar and graduate student Soroush Mirkiani, at the University of Alberta, for their invaluable support and guidance throughout this project.

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HYBRID FES-ARMEO®SPRING SYSTEM FOR STROKE REHABILITATION: A USER-CENTERED DESIGN APPROACH

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Introduction: Functional electrical stimulation (FES) and various upper extremity exoskeletons, such as Armeo®Spring, are widely utilized in modern stroke rehabilitation to improve motor control and range of motion [1]. Studies combining FES and exoskeletons for post-stroke rehabilitation, creating hybrid systems, report promising results in improvements of upper extremity range of motion. However, studies suggest that future research should include specific functional abilities such as reaching and grasping [2]. Furthermore, research yields positive results regarding meeting clinical requirements and personalizing hybrid solutions, when directly involving users [3]. This highlights the importance of applying a user-centered design approach to meet user needs when developing hybrid systems.
Methods: The needs of patients and therapists when using Armeo®Spring (Hocoma, Switzerland) during upper-limb rehabilitation, as well as their wishes to combine FES and Armeo®Spring, were gathered using a user-centered design approach. Data was collected through observations of training sessions followed by interviews with 3 stroke survivors undergoing rehabilitation. Furthermore, a focus group interview with 6 physiotherapists from two stroke rehabilitation units was conducted. Data were analyzed and functional requirement specifications for a hybrid FES-Armeo®Spring system were developed. A system prototype was built and evaluated through case-specific tasks associated with the requirement specifications and their success criteria. This first evaluation involved two physiotherapists who participated in Think-aloud interview sessions with a healthy participant.
Results: Regarding the users' needs, the therapists found Armeo®Spring less suitable for patients with very limited wrist mobility or grip strength. Therapists expressed interest in integrating FES with Armeo®Spring as a hybrid system to amplify wrist movements and grip force during hand exercises. In separate interviews, patients expressed the need for a similar solution and an openness toward implementing electrical stimulation as part of their rehabilitation. The main requirement specifications are presented in Table 1. The evaluation of a first Proof-of-Concept showed that the functional requirement specifications were met and that the hybrid system would benefit from enhanced synchronization between FES and Armeo®Spring.
Discussion and conclusion: This study showcases the potential of integrating FES with Armeo®Spring to address limitations experienced by users in clinical practice. The user-centered design process served to identify key needs crucial for prototype development. The results from the evaluation contributed to new requirements specifications for future iterations of the hybrid system.

Table 1: Functional requirement specifications for the hybrid FES-Armeo®Spring system.

	Functional requirement specifications
1	The system must combine the use of Armeo®Spring and FES on the same arm. Both systems must operate simultaneously and synchronously.
2	FES must support wrist movements, increasing dorsal and palmar flexion when the patient attempts these movements while training with Armeo®Spring.
3	FES must support increased grasp function when the patient attempts to flex one or more fingers while training with Armeo®Spring.

Acknowledgments: The authors would like to thank the participating patients and physiotherapists. This study was funded by Simon Fougner Hartmanns Familiefond (ID: 2023-0029).

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TOWARDS THE PARTICIPATION TO CYBATHLON 2024 FES-BIKE RACE: A CASE REPORT

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Introduction: Since its foundation in 2013, Cybathlon competition has aimed to promote inclusion and the use of assistive technologies in daily life. The lessons learned through the user-centered design process provide useful insights for the scientific community. This work presents the journey towards Cybathlon 2024 of the team from Politecnico di Milano that participated in the Functional Electrical Stimulation (FES)-bike race. In this discipline, individuals with complete spinal cord injury (SCI) must cover a distance of 1960 m within 8 min using FES-induced cycling.
Methods: A commercial recumbent passive trike (Catrike 700) was instrumented with an 8-channel neuromuscular stimulator (P24-Science, Hasomed GmbH) and a crank position encoder to perform FES-cycling. The custom software comprises a proportional integral (PI) controller that modulates the current amplitude to maintain a desired cadence [1]. Stimulation frequency and pulse width were kept fixed in the range of 30-40 Hz and 400-500 µs, respectively. A SCI subject (43 years, Asia A, T5, 5.6 years from lesion) was trained for the race (Ethical Committee approval Nr 50/2023, Politecnico di Milano). Angular ranges were optimised according to [2] and validated in terms of time to PI saturation and steady-state cadence. A training protocol based on the principle of periodisation - preparation and competitive phases - was implemented to prepare the pilot with 8-min race tests performed periodically to monitor training progress.
Results: Optimised stimulation ranges and constant training led to a 99% increase in time to PI saturation, reduced error between steady-state mean and target cadence (-42%). Figure 1 shows the linear periodization trend, with reduced training volume and increased speed over time. Race tests recorded an overall improvement, approaching the 1960 m target by the competitive phase. A notable performance decline was observed between July and September. The periodization aimed to maximize the pilot's potential for the race, successfully achieving this goal. The pilot qualified for the final, secured third place, and set a personal best by covering the 1960 m target distance in 7 min and 34 s.
Discussion and conclusion: Stimulation ranges proved to be effective in comparison with the previous used ones and were used during trainings and race. The overall aim of the training program was maintained but a flexible approach was essential to handle interruptions. The customized approach adopted for the preparation of the race proved to be valuable and, together with the consistency of the pilot, led to the achievement of the competition's target. This work showed how personalization, planning, and adherence can yield exceptional in improving FES-cycling performances. Future developments will focus on the design of a hybrid FES-motorised trike for outdoor training, including automatic adaptation of the stimulation strategy to manage muscle fatigue.

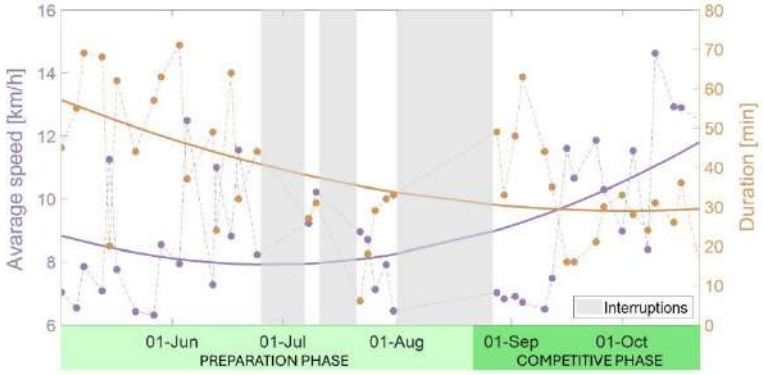


Figure 1: Stimulation time and average speed maintained during the training session. Respective trends in solid line.

Acknowledgments: This work was funded by INAIL (Istituto Nazionale per l'assicurazione contro gli Infortuni sul Lavoro, Italy) - FESleg project (PR19-RR-15), and by Cariplo Foundation and Lombardy Region - Activ-E^3 (Everyone, Everywhere, Everyday) project (CUG: C13C21000200005). We thank the pilot for his dedication and valuable insights, all the team members for their contribution, and Axelgaard Manufacturing Ltd for donating the stimulation electrodes.

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Evaluation of usability, acceptability, user experience and human-device interaction of a Hybrid FES-Motorized trike for Sport-Therapy

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Introduction: Physical activity is crucial for improving quality of life, especially for physically frail individuals who often lead sedentary lifestyles, worsening their health. Technologies can enable safe and accessible physical activity. Functional Electrical Stimulation (FES) cycling has been shown to induce motor relearning [1] and increase muscle size and force generation [2]. This study presents an evaluation of the usability, acceptability, user experience, and human-device interaction of a Hybrid FES and motor-assisted trike designed for Sport-Therapy.

Methods: Elderly subjects (age>65 years) without motor disability (Ethical Committee approval Nr 41/2024) were recruited to test the Hybrid Trike (HT), a commercially available recumbent Trike (Catrike 700) instrumented with an 8-channel neuromuscular stimulator (P24-Science, Hasomed GmbH) and a DC electric motor [3]. FES, applied to the Quadriceps, Hamstrings, Tibialis A. and Gastrocnemius, can be manually adjusted by the user at a tolerated level to enhance proprioception and stimulate blood circulation, while motor assistance ensure a minimum cycling cadence without resisting the user's active contribution. Usability, acceptability, user-experience (UX) and human-device interaction were investigated employing 5 questionnaires: Technological Acceptance Measure 3 (TAM-3), System Usability Scale (SUS), User Experience Questionnaire (UEQ), an ad hoc questionnaire assessing human-device interaction from both physical and psychological perspectives, and the Net Promoter Score (NPS) to assess overall satisfaction and likelihood of recommending the device. The protocol consisted of: a) preliminary assessment (T0) with baseline data collection; b) 2 training sessions with HT, the first indoors and the second outdoors; c) T1 assessment via questionnaires.

Results: 10 subjects (age: 69.4±5.06 years; 4 female, 6 male) were enrolled. The HT achieved an average SUS score of 92.5 (7.5) out of 100, indicating excellent usability. The UEQ assessed various aspects of user experience, with scores documented in Table 1 (left), demonstrating a generally pleasant, stimulating, and visually engaging experience. The ad hoc questionnaire evaluated seven specific items, with corresponding scores presented in Table 1 (right). The TAM-3 yielded an acceptance score of 6.17 (0.30) on a 7-point Likert scale (1: total disagreement, 7: total agreement), while the Net Promoter Score (NPS) registered at 60 (out of 100), suggesting overall satisfaction.

Discussion and conclusion: Preliminary findings indicate that the Hybrid Trike technology is highly accepted (TAM-3 scores), while the SUS results align with benchmarks for user-friendly and high-performing systems, ranking within the top 10% of results. The UEQ results highlight the system's ability to provide an engaging experience as well as users' appreciation of the design and functionality. The ad hoc questionnaire and NPS confirm high user satisfaction, with participants reporting a straightforward positioning process and an intuitive interface. Physical effort levels were well-aligned with the participants' capabilities, allowing smooth and efficient movement with minimal fatigue. These findings support the Hybrid Trike potential as an effective tool for promoting physical activity among ageing populations.

Table 1: Item scores of the UEQ (score range: -3/+3) and the ad-hoc questionnaire (5-point Likert Scale, 1: total disagree, 5: total agree; score range 1-10 for item "Pain during positioning and use"). Score presented as median (interquartile).

Items UEQ	Score	Items ad-hoc questionnaire	Score
Attractiveness	3.00 (0.17)	Setup and Accessibility	4.75 (0.44)
Perspicuity	3.00 (0.00)	Perceived Benefits	4.67 (0.33)
Efficiency	2.75 (0.63)	Comfort	4.25 (0.75)
Dependability	2.38 (0.44)	Usability and Interaction	4.50 (0.33)
Stimulation	2.75 (0.19)	Physical Effort	2.67 (0.50)
Novelty	2.00 (1.06)	Fatigue	2.27 (1.68)
		Pain during positioning and use	0.00 (0.00)

Acknowledgments: This work was performed within the Activ-E[3] (Everyone, Everywhere, Everyday) project, funded by Cariplo Foundation and Lombardy Region (CUG: C13C21000200005). We thank Axelgaard Manufacturing Ltd for donating us the stimulation electrodes and subjects who took part to the study for the valuable time and commitment.

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EXPLORING THE MECHANISM OF UPPER LIMB FUNCTIONAL ELECTRICAL STIMULATION THERAPY IN STROKE PATIENTS U-SING FUNCTIONAL NEAR-INFRARED SPECTROSCOPY

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Introduction: Previous studies have demonstrated that mechanical load training enhances motor performance after stroke, accompanied by increased activation in the primary motor cortex (BA4) and premotor cortex (BA6), as detected by fNIRS [1]. Functional electrical stimulation (FES) facilitates goal-directed movements and promotes CNS reorganization in response to peripheral stimulation [2,3]. While electrical stimulation boosts cortical excitability, the effects of FES-induced motor learning on specific brain regions remain unclear[4]. This study used FES-assisted upper limb training in stroke patients, with fNIRS monitoring brain activity, to explore FES's mechanisms and its rehabilitation potential.

Methods: Two post-stroke patients performed repetitive affected arm lifts at 2 Hz under three resistance levels (0, 3.0–4.3, 5.8–8.6 lb), completing 12 sets of 10–12 reps each. FES was applied to posterior deltoid, biceps brachii, triceps brachii, and brachioradialis muscles (100 μs, 20 mA, 30 Hz, symmetric biphasic, 2 s stimulation, 100 ms ramp), automatically adjusted via inclinometer. Multi-channel fNIRS monitored cortical activity during training.

Results: In subject 1, β coefficient in bilateral BA4 and BA6 channels significantly increased during the transition from no weight to light weight, while most channel β coefficient declined from light to heavy weight, except for a few channels on the affected side (primarily in BA6) that continued to increase. In subject 2, some BA4 and BA6 channels showed increased β coefficient with increasing load, with a slight increase in a few BA6 channels during the transition from light to heavy weight

Findings and thoughts:

1.Cortical regions involved in motor output and planning show increased neural activity with higher loads during FES-assisted tasks, but excessive load may reduce recruitment due to fatigue and distraction.

2.Further control group studies are needed to clarify the differential effects of FES on cortical areas.

3.Resistance changes during movement may burden stroke patients more than expected. Quantifying performance under different resistances is essential for future studies.



Figure 1: FES electrode and fNIRS.

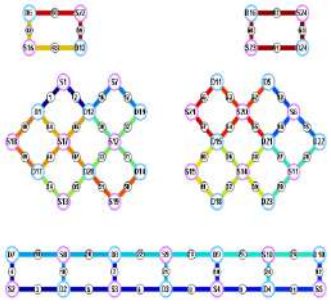


Figure 2: fNIRS channel.

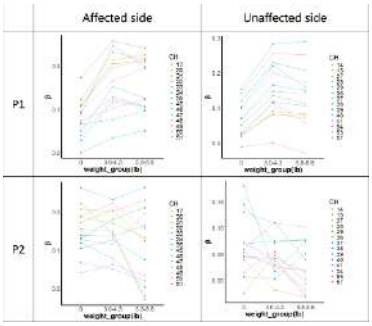


Figure 3: Beta coefficient.

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The combination of motor imagery and transcranial magnetic stimulation increases corticospinal excitability of the tibialis anterior muscle but not with motor imagery alone.

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Introduction: Motor imagery (MI), the mental simulation of movement, modulates corticospinal excitability (CSE) [1] and is widely used in rehabilitation. However, its effects can vary depending on the MI task and the targeted muscle. Our recent study demonstrated that MI of knee extension facilitated CSE of the rectus femoris (RF), an agonist muscle, and the tibialis anterior (TA), which is not directly involved in knee extension [2]. This study aimed to investigate the effects of combining MI with transcranial magnetic stimulation (MI+TMS) on CSE of lower limb muscles.

Methods: Twenty healthy graduate students (five females) were recruited for the study and they had not engaged in any exercise prior to the experiment. They were seated, and electromyographic (EMG) activity was recorded from the right RF, biceps femoris (BF), TA, and soleus (SOL) muscles. The CSE was assessed by measuring motor-evoked potentials (MEP) amplitudes elicited via TMS applied to the primary motor cortex. The stimulation site was the RF hotspot, with the intensity set at 1.2 times the resting motor threshold of RF. The neuro-navigation system was used throughout the experiment, and the coil position was kept at the same location. In the MI+TMS condition, participants alternated between resting and MI states every 4 seconds while avoiding any actual muscle contractions. During the MI state, participants performed MI of maximal effort knee extension, and TMS was delivered during this phase. A total of 120 repetitions were performed. CSE evaluations at rest were conducted before the intervention (Pre), immediately (Post 0), 15 minutes (Post 15), and 30 minutes after (Post 30). At each time point, 12 MEPs were recorded, and their peak-to-peak amplitudes were averaged (Figure 1). Additionally, the MI-only condition was conducted to examine the effect of MI alone. The MI-only condition followed identical procedures, except no TMS was applied. Since MEP data were not normally distributed, the Friedman test and Steel post hoc test were used to compare MEP amplitudes between Pre and Post measurements.

Results: The MEPs of RF, BF, and SOL showed no significant changes at any time point following MI+TMS ($p > 0.05$). However, the MEPs of TA were significantly larger at Post 0 and Post 15 compared to Pre ($p < 0.05$) (Table 1). In the MI-only condition, no MEP changes were observed in all muscles.

Discussion and conclusion: Contrary to expectations, MI+TMS did not enhance RF CSE, despite the RF being the agonist in knee extension imagery. Interestingly, the intervention enhanced TA CSE at Post 0 and Post 15, suggesting a preferential effect on TA, a muscle not directly involved in the imagined movement. These findings align with previous research showing that MI of knee extension can facilitate TA CSE. However, the specific effects of MI+TMS observed in TA indicate that this muscle is more responsive to neuroplastic changes induced by this combined intervention. On the other hand, the lack of RF CSE changes may indicate lower plasticity in this muscle, despite optimized MI+TMS parameters. These findings enhance our understanding of muscle-specific plasticity mechanisms.

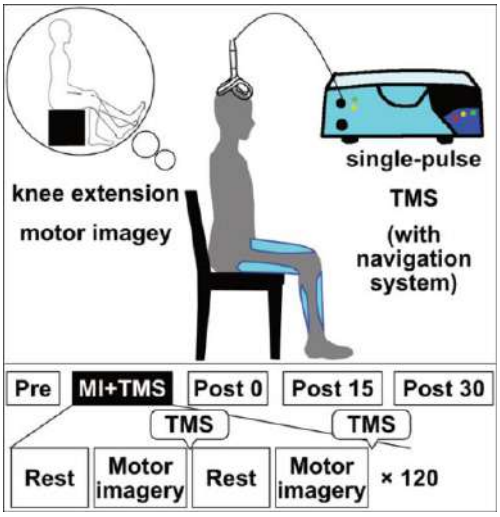


Figure **1**: Experiment procedure

Table 1: Changes in average MEP amplitudes expressed as a percentage of those measured before intervention (median and range). Asterisks denote significant differences compared to those measured at Pre (Steel test)

	MI+TMS condition (% Pre)		
	Post 0	**Post 15**	**Post 30**
RF	103.1 (55.2 – 329.6)	103.0 (40.1 – 292.3)	95.6 (41.9 – 313.9)
BF	119.0 (35.6 – 289.7)	129.4 (39.0 – 205.3)	168.6 (34.4 – 346.5)
TA	**104.3 * (50.5 – 302.2)**	**122.3 (52.2 – 180.1)**	128.0 (52.0 – 349.7)
SOL	106.5 (57.1 – 173.4)	104.6 (164.2 – 67.9)	117.8 (63.9 – 362.0)

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Short-term somatosensory-motor effects after transcranial and peripheral magnetic stimulation of the extensor carpi radialis muscle: a pilot study in healthy adults

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Introduction: Similarly to electrical stimulation approaches, magnetic stimulation induces an electric current used to activate specific body areas. Magnetic neurostimulation is manifested in diagnostics and research and used for neurological and psychiatric disorders therapy. Post-stroke therapies mainly focus on motor aspects, and integrative sensorimotor therapies are limited. Knowledge about the lasting effects of magnetic stimulation on somatosensory-motor networks can help to shed some light to design effective therapeutic applications of the upper extremities in patients after a stroke. This is especially relevant regarding the sequencing of these applications in a rehabilitation setting. The aim was to assess the short-term somatosensory-motor effects of transcranial and peripheral Theta-Burst stimulation (TBS) [1] on the Extensor carpi radials (ECR) muscle in healthy adults. ECR was investigated as wrist extension movements are frequently stimulated in clinical interventions to enhance motor function and to reduce spasticity of wrist flexor muscles.
Methods: Eight young healthy participants (2 men; age 28±2.89 years) received four different sessions on different days of either continuous TBS (cTBS), intermittent TBS (iTBS), peripheral intermittent TBS (pTBS) or no intervention.
Both, cTBS and iTBS were applied over the left primary motor cortex addressing the ECR. pTBS was applied over the right ECR muscle belly. Motor evoked potentials (MEPs) and somatosensory evoked potentials (SSEPs) were assessed before (t0) and after (t1) the intervention. All examinations were conducted in a semi-recumbent position, with the arms resting on an armrest to ensure a relaxed position. The period between the sessions was at least 48 hours, and the order of the individual sessions was randomized. Two-way repeated-measures ANOVAs were used for statistical analysis with alpha=5%.
Results: Regarding MEPs, transcranially applied TBS showed no significant modulatory effects compared to peripheral applied TBS (see Fig.1 left). Regarding SSEPs, mean peak-to-peak amplitudes of early SSEP components of the right radial nerve showed no significant differences in SSEPs when TBS was applied peripherally compared to transcranial stimulations (see Fig.1 right).
Discussion and conclusion: In this pilot study, theta-burst stimulation of the right ECR muscle did not lead to a significant short-term modulatory effect on MEPs or SSEPs in healthy participants, neither when applied transcranially nor when applied peripherally. This is contradictory to findings that iTBS leads to an increase and cTBS to a decrease in motor cortex excitability [2]. The order of recording the outcome measures was randomized in our setup, i.e., either MEPs or SSEPs first. When taking this into account, greater effects on SSEPs were found following pTBS stimulation when SSEPs were recorded first. This finding needs to be further investigated, and discussed regarding the time course of the effects and, with this, the effectiveness of these interventions.

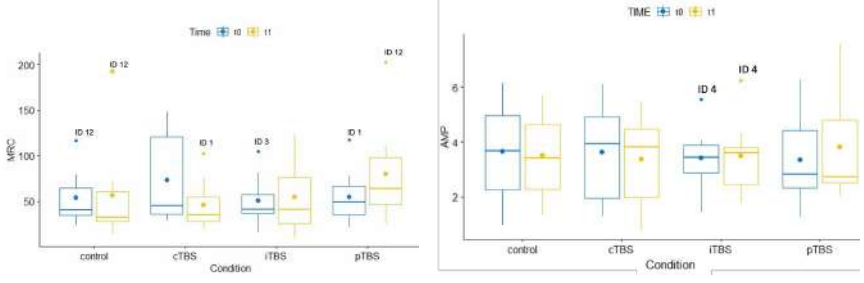


Figure **1**: left: MEP recruitment curve (% of resting motor threshold); right: SSEP amplitudes [µV], peak-to-peak amplitudes.

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Enhanced Neuromodulatory Effects of Transspinal Stimulation on Spinal Excitability in Incomplete Spinal Cord Injury

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Objective:
To evaluate the neuromodulatory effects of non-invasive Transspinal Stimulation (TSS) on spinal excitability in individuals with incomplete spinal cord injury (SCI) and compare the effects to a sham intervention.

Design:
This was a longitudinal randomized home-based clinical pilot study where motor evoked potentials (MEPs) were captured at three time points over a 21-week period. Participants were either randomized into a TSS and blood flow restricted exercise (BFRS) [1] intervention group or a sham TSS and BFRS arm. Both groups completed telehealth-supervised, home-based training, including forearm electrically evoked blood flow-restricted exercise and task-specific training, three times weekly for 16 weeks.

Participants:
Six participants with chronic incomplete SCI [AIS B-D], aged 37 ± 14.6 years, with a time since injury of 2–23 years, were enrolled in the study. Four participants received TSS+BFRS, and the other two participants were in the sham TSS and BFRS arm.

Intervention:
In the training and education phase (first 4 weeks), the TSS group received active stimulation with two cathodal electrodes placed between the interspinous processes of C3-C4 and C6-C7, and two rectangular electrodes placed bilaterally over the clavicles. In contrast, the sham group received low-intensity stimulation (1 mA, 5 Hz, 100 µs phase duration) with the same electrode setup. During testing phases (baseline 1 [BL1], baseline 2 [BL2], and post-intervention 1 [P1]), both groups received identical stimulation parameters (1 Hz, biphasic pulse of 2 ms, and stimulation intensity up to 40 mA). BFRS pressure was determined by measuring resting blood pressure and then inflating the cuff 30% higher than the systolic blood pressure of the participant, NMES was then applied during training. BFRS protocol remained consistent across both groups throughout the study. Wireless TRIGNO electromyography (EMG) sensors recorded MEPs from the triceps, biceps, wrist flexors, and wrist extensors bilaterally.

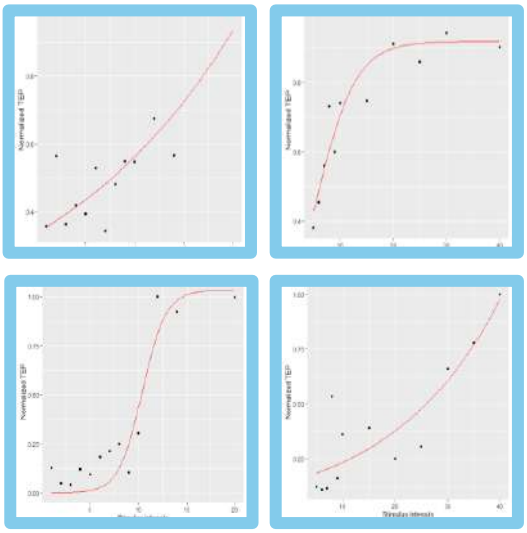


Figure 1. Triceps (top) and wrist flexor muscles (bottom) recruitment curves at BL (left) and P1 (right).

Results and Conclusion:
Recruitment curves (Fig.1) [2] in the TSS and BFRS group demonstrated a leftward shift at P1 for the triceps, biceps, and wrist flexor muscles, with a trend toward plateauing, suggesting potential changes in spinal excitability. In contrast, wrist extensor curves exhibited a non-plateauing rise with increasing stimulation intensity, possibly reflecting an adaptive response. Recruitment curve dynamics in the sham group were analyzed similarly, though data analysis for the sham arm is still ongoing at the time of submission. These findings highlight distinct recruitment curve dynamics in participants receiving TSS and BFRS, with notable changes in wrist extensor behavior that may reflect adaptive neuromodulatory responses. This study provides insights into the potential of TSS and BFRS to modulate spinal excitability and enhance upper extremity motor function in individuals with incomplete SCI.

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DEVELOPMENT OF A HYBRID FES-ARMEO®SPRING SYSTEM FOR ENHANCING STROKE REHABILITATION

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Introduction: Stroke is a leading cause of long-term disability, often impairing upper limb function. Despite advances in rehabilitation, functional recovery remains limited. Functional Electrical Stimulation (FES) supports motor recovery, while exoskeletons like Armeo®Spring enable intensive movement therapy. Hybrid systems for upper limb rehabilitation integrate FES and passive orthosis for grasping, and FES and passive exoskeletons/active robotics for wrist flexion and extension and reaching tasks [for reviews see 2-3]. The combined use of FES and exoskeleton systems for upper-limb rehabilitation remains however insufficiently explored [2]. This study focuses thus on the integration of FES with Armeo®Spring to improve the training of wrist and grasping functionality of severely affected stroke patients by augmenting their attempted movements.

Methods: A hybrid system that synchronizes FES and Armeo®Spring for coordinated wrist flexion, extension, and grasping was developed. FES was delivered via the computer-controlled B-Stim device (Global Electronics Solutions, Serbia). Armeo®Spring provided repetitive, task-oriented training while supporting the arm's weight. An IMU (x-IMU3, x-io Technologies, UK) detected movement attempts. For controlling FES, the IMU was mounted on the ipsilateral hand when training wrist motions (Figure 1) and on the contralateral hand when training grasping, implementing a Contralaterally-Controlled FES (ccFES) approach. The movement sensitivity was controlled by the physiotherapist. MATLAB was used to develop custom algorithms for processing sensor data and controlling the stimulation channels (pulse characteristics and timing of FES activation). A Proof-of-Concept of the system was evaluated by physiotherapists, who were responsible for administering the training, and healthy participants.

Results: The hybrid system could successfully detect the initiation of grasping, wrist flexion and extension, and elicit FES enabling task completion in the virtual game environment. For wrist flexion/extension, proper IMU calibration in consonance with Armeo®Spring's desired game was essential to ensure a synchronized FES activation. For grasping tasks, the ccFES required that the contralateral arm rested along the ipsilateral leg.

Discussion and conclusion: A hybrid FES-Armeo®Spring system to improve wrist range of motion and grasping function in severely affected post-stroke patients was developed. The real-time sensor-driven FES combined with Armeo®Spring resulted in synchronized movement support. The system must now undergo testing with severely impaired stroke patients.

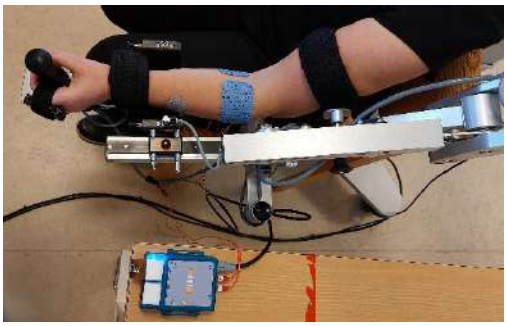


Figure **1**: Hybrid FES-Armeo®Spring System for wrist motion.

Acknowledgments: The authors would like to thank the healthy participants and physiotherapists. This study was funded by Simon Fougner Hartmanns Family Foundation (ID: 2023-0029) and Melsen Foundation.

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TRADING CONTACT: STUDYING A WEARABLE REHABILITATION DEVICE IN CLINIC WITH MARKERLESS MOTION CAPTURE

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Introduction: Rehabilitation has been described as a cycle which relies on assessment [1], and for conditions like stroke, clinicians commonly rely on observation-based assessments that offer convenience, timeliness, and low-expense. The recognized drawbacks of observation include subjectivity, coarse resolution, and floor/ceiling effects. These drawbacks are motivation to integrate into clinical practice more objective, instrument-based assessments such as by wearable sensors. However, other rehabilitation technologies worn by patients (e.g. orthoses, e-stim devices) create a practical barrier to wearable sensors. To circumvent this barrier, we investigate a non-contact, instrument-based approach to patient assessment.

Methods: In a repeated measures case study, a stroke survivor with severe chronic left upper limb impairment was invited to an outpatient PM&R clinic and asked to perform an activity (transferring a cloth napkin) while wearing an investigational dynamic wrist-hand orthosis for assisted finger extension. During 12 activity trials, two dichotomous conditions (right/left upper limb, with/without orthosis) were evenly represented among the trials. To assess kinematics, we employed a markerless motion capture system developed by our team, which utilizes computer vision to extract upper limb kinematic metrics, i.e. movement time (MT) and trunk displacement (TD), from videos without need for body-worn sensors or adhesive markers [2]. Our primary objective was to investigate feasibility of this approach. Our secondary objective was to explore the effect of orthosis condition on comparative kinematic analyses of the affected versus less-affected upper limb.

Results: For all trials, the markerless motion capture system successfully extracted time-series 3-dimensional position data of keypoints approximating the joint centers of the shoulders, elbows, and wrists. For 11 trials, the kinematic metrics of MT and TD were successfully computed, and 1 trial was excluded due to a bystander inadvertently captured in background of patient's activity. For computed TD, regardless of brace condition, a significant difference between the affected and less-affected upper limb was found ($p<0.001$ and $p=0.005$ for no-brace and brace condition, respectively). For computed MT, a significant different between upper limbs was found for the no-brace condition ($p=0.002$) and between-limb difference for the brace condition failed to reach significance ($p=0.08$).

Discussion and Conclusion: We investigated the feasibility of a markerless motion capture system to achieve non-contact assessment of upper limb kinematics in a stroke survivor wearing an orthosis. We expected to find significant differences between the affected and less-affected upper limb for both TD and MT regardless of brace condition. The lack of significant findings for MT for the brace condition is likely because MT relies more on the distal upper limb movement (wrists), which is challenged by line-of-sight interference due to orthosis. In contrast, TD depends more on proximal upper limb movement (shoulders). Study limitations include the case study design, low activity repetitions, and limited kinematic metric outcomes. This case study of the post-stroke upper limb suggests that markerless motion capture may be a promising avenue for non-contact assessment of select kinematic metrics now. As future iterations of the technology develop, we look forward to further evaluating its potential among different patient populations, scenarios, and activities.



Figure 1: While wearing an orthosis, a stroke survivor undergoes non-contact kinematic assessment using a markerless motion capture system.

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IMREA's recommendations for Neuromuscular Electrical Stimulation (NMES)

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Introduction: Neuromuscular Electrical Stimulation (NMES) is a widely used technique in rehabilitation, leveraging electrical currents to induce muscle contraction. This method has demonstrated application in various clinical settings, particularly in enhancing functional outcomes for individuals with neuromuscular impairments. This study explores optimized NMES stimulation approaches, focusing on research and clinical applications conducted at Instituto de Medicina Fisica e Reabilitacao (IMREA), Hospital das Clinicas HCFMUSP, Faculdade de Medicina, Universidade de Sao Paulo.
Methods: This study synthesizes IMREA's NMES rehabilitation protocols, focusing on optimized electrode placement and progressive overload training into the sessions. The motor point technique involves positioning the electrode over the skin region most responsive to NMES. At IMREA, we not only identify the motor point but also map all sites that trigger muscle contractions, whether weak or strong. These points collectively define the motor area (Fig. 1). Accurate electrode placement within this area enhances muscle contraction, optimizing therapeutic outcomes. Additionally, a progressive overload protocol (Fig. 2) is employed, wherein the load applied during joint movements is gradually increased. Detailed methodology on the utilization of electrical stimulation in conjunction with other clinical interventions is available in Imamura et al. [1].
Results: Induced contractions at 20Hz, targeting aerobic type I muscle fibers, combined with strategic electrode placement and progressive resistance, can be effective in improving functional outcomes across a variety of patient populations as demonstrated by previous research at IMREA, including those with COVID-19 [1], cerebral palsy [2], and paraplegia [3]. While motor points are the specific skin area where the target muscle is best stimulated, the motor area increases the general force produced, which can be associated with progressive resistance in rehabilitations protocols.
Discussion and conclusion: These NMES approaches has demonstrated significant therapeutic benefits.



Figure 1: Motor area for electrode placement.



Figure 2: Progressive overload.

Acknowledgments: We would like to thank engineer Milton Seigui Oshiro for his guidance, effort and dedication in transmitting his knowledge to IMREA health professionals. An inspiring force whose ideas remain even after his death.

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Characterization of the Posterior Root-Muscle Reflex in Healthy Individuals of Different Ages

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Introduction: The Hoffman's (H)-reflex is evoked by electrically stimulating a peripheral nerve. Primary afferents in the peripheral nerve are excited and monosynaptically activate spinal motoneurons, resulting in a reflex response that can be recorded in the homonymous muscle using electromyography (EMG) [1]. The H-reflex threshold, which is the current required to elicit the H-reflex, increases with age, indicating reduced spinal cord excitability as people get older [2]. The posterior root-muscle (PRM) reflex is a compound of the H-reflex and cutaneous reflexes [3]. The PRM reflex is elicited by electrically stimulating the dorsal roots of the spinal cord, which contain afferent fibers, using transcutaneous spinal cord stimulation (tSCS). Previous work showed that individuals with lower-limb amputation exhibit reduced spinal cord excitability, as determined by increased stimulation thresholds required to evoke the PRM reflex [4]. This means that the analysis of spinal reflexes, such as the PRM reflex, can be used to determine how spinal cord excitability changes after neural injury. However, unlike the H-reflex, it remains unclear how the PRM reflex threshold changes with age. This study aims to characterize PRM reflex thresholds in healthy participants of different age groups to develop a database to compare spinal cord excitability changes with individuals with neural injury.

Methods: PRM reflexes were evoked using a single 1 ms-long monophasic, cathodic square pulse delivered through adhesive electrodes placed lateral to the T12-L1 vertebrae. A return electrode was placed on the ipsilateral anterior superior iliac spine. PRM reflexes were recorded in 21 neurologically-intact participants (11 female; 23 - 49 years old). Wireless EMG sensors were placed over the soleus muscle on the ipsilateral leg, relative to the stimulating electrode. Stimulation was first delivered at a sub-threshold level, then increased in 5 mA increments until PRM reflex responses first appeared in the EMG recording (threshold), after which the threshold was identified with 1 mA precision. Stimulation was then increased in 5 mA increments until the responses no longer increased in amplitude (maximum).

Results: PRM reflex thresholds were 35 ± 9.9 mA for ages 20-29 (n = 14, 40 ± 19 mA for ages 30-39 (n = 5), and 42 ± 7.8 mA for ages 40-49 (n = 2). Linear regression of the PRM reflex thresholds over age resulted in a correlation coefficient of R = 0.20. There was an increase in PRM thresholds in older participants; however, the individuals in this study were relatively young, with fewer participants in the older age ranges. Additional reflex thresholds per decade are expected to strengthen this correlation. An example reflex recording at threshold and at maximum are shown in Figure 1.

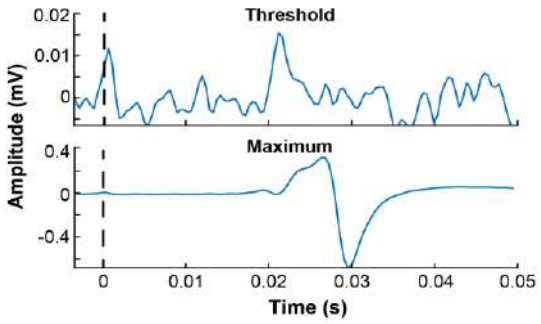


Figure 1: Example of single PRM reflex traces recorded from the soleus at threshold (top) and maximum (bottom) stimulation amplitudes.

Conclusions: By characterizing how PRM reflex thresholds change with age, we can develop a better understanding of how spinal cord excitability changes over time in healthy individuals, as well as compare thresholds from healthy individuals to those with neural injury. Understanding how the spinal cord changes with age and neural injury is foundational to developing neurotechnologies to improve sensorimotor function.

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Optimization of Intracortical Microstimulation with Ultra-thin, Ultra-micro-electrode Arrays via Spatial Current Steering

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Introduction: Intracortical microstimulation (ICMS) offers a promising pathway to restore sensory functions for individuals with paralysis, primarily by targeting the primary somatosensory cortex (S1). However, the longevity and stability of ICMS are hindered by chronic foreign body responses (FBR) that lead to device encapsulation by immune cells and increased sensory thresholds over time. To mitigate these effects, ultramicroelectrode arrays (UMEAs) have been designed to reduce device encapsulation and therefore improve long-term device performance. For stimulation applications, one of the challenges for smaller electrode-site areas is the increased current densities at the electrode which can damage the device or surrounding tissue. In this study, we explore the capability and capacity of ultra-thin ultramicroelectrode arrays (G3 UMEAs) capable of delivering effective stimulation via spatial current steering while mitigating the foreign body response. The overarching goal of the work is to develop multichannel ultramicroelectrode arrays suitable for chronic neurostimulation.

Methods: G3 ultramicroelectrode devices were custom designed with 19 electrodes of 5 µm to 20 µm diameters (19.63 μm^2 and 314.16 μm^2, respectively) as seen in Figure 1. To improve charge-storage capacity, electrodes were coated with a sputtered iridium oxide film (SIROF). The electrodes were implanted to a depth of 1700 µm in the somatosensory cortex. Stimuli were delivered to electrode sites at 320 Hz using 650 ms pulse trains with 0.2 ms phase duration and 0.04 ms interpulse intervals.

A modified conditioned avoidance behavioral paradigm [1] was used to determine detection thresholds in rats. Water-deprived rats were monitored for licking patterns, with safe trials (controls) and warning trials (ICMS stimulus). Detection thresholds were determined with an adaptive algorithm that decreased stimulus amplitude if the animal successfully detected the stimulus ("hit") and increased if stimulus detection was unsuccessful ("miss"). The magnitude of the amplitude change decreased with each trial. This pattern was repeated until three reversals (hit followed by miss, or vice versa) was recorded at which point the detection threshold was calculated using the average of the stimulation amplitude for the last five trials.

Results: Chronic behavioral responses to neural stimulation were observed, with consistent thresholds achieved by stimulating multiple channels simultaneously. Additionally, reducing the electrode site area stimulated shows promise in improving stimulation efficacy.

Discussion and conclusion: These insights highlight the ability of ultra-thin microelectrode arrays to evoke behaviorally relevant stimulation of the somatosensory cortex and pave the way for further innovations in brain-machine interface technology to enhance sensory feedback for persons with paralysis.

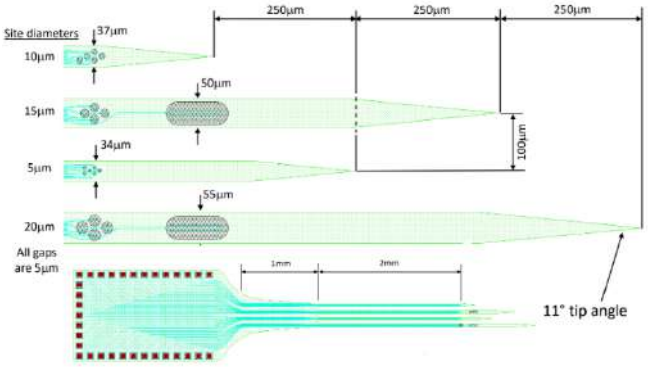


Figure 1: G3 UMEA Design.

Acknowledgments: This material is based upon work supported by the National Institutes of Health under Grant 1U01NS126052.

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FES Bike Race preparation to Cybathlon 2024 by EMA team: a short case report with inclusion of new muscle group

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Introduction: In FES Cycling, alternating stimulation of the legs generates knee extension and flexion movements (Jaeger et al., 2023). The quadriceps are the primary muscles stimulated for knee extension, supported by the hamstrings and glutes to enhance efficiency. The Cybathlon, a leading FES Cycling competition, featured the EMA team in 2016, 2020, and 2024. After challenges with hamstring inclusion in 2016 and 2020, a specific protocol was developed for 2024 to optimize their contribution, improve performance and also impact on a better quality of life for the pilot.

Methods: The pilot, a 46-year-old man (1.70 m, 78 kg) with a 12-year T9 spinal cord injury (AIS A), followed a protocol to incorporate hamstrings into FES Cycling, aiming to reduce muscle spasms and stiffness. Training occurred in two phases. From March to June, the program included neuromuscular electrical stimulation for low-frequency strengthening (targeting quadriceps, hamstrings, tibialis anterior, and triceps surae), fatigue training, FES Cycling (2 laps of 8 minutes), and resistance training. From July to September, it focused on increasing intensity and optimizing cycling performance with extended sessions (3 laps of 8 minutes) and shorter, high-intensity sessions (3 laps of 4 minutes). To assess hamstring influence, a standardized warm-up protocol was used, involving passive stretching, assisted pedaling, and FES Cycling. On two alternate days, randomized trials were performed with a 10-minute interval: one activating only the quadriceps and the other combining quadriceps and hamstring activation. This approach improved muscle efficiency, cycling performance, and hamstring functionality.

Results: The combined activation of the quadriceps and hamstrings (figure 1) led to improvements across all parameters analyzed compared to quadriceps-only activation. There was a 3.73% increase in the average distance covered (from 670 m to 695 m), a 5.53% increase in average power output (from 16.45 W to 17.36 W), and a 1.01% improvement in average cadence (from 51.62 rpm to 52.14 rpm) (table 1). These findings suggest that the inclusion of the hamstrings contributed to a more efficient and consistent performance in FES Cycling.

Discussion and conclusion: The proposed protocol contributed significantly to the inclusion of isquitobians during FES cycling mainly due to the reduction of spams. Throughout of the preparation of 2016 and 2020 one of the biggest challenges we found was the high amount of spasms of the hamstrings, being this a limitation for better performance. One of our goals for Cybathlon 2024 was the inclusion of hamstrings. Mainly because it reduces fatigue during the race, allowing for a better race. After the insertion of the hamstrings, focus on fixing the most appropriate pulse width during stimulation. Ranging from 15 to 35% of the pulse width used in the quadriceps. We kept our protocol until the end of the preparation, and had our best participation in an edition of Cybathlon, covering 1.4 km in 8 minutes without interruptions.



Figure **1**: Position of adhesive electrodes.

Table 1: Comparison of runs with different muscles activated

Item	QUA	QUA + HAM	%
Distance (m)	670	695	3.73
Power (W)	16.45	17.36	5.53
Cadence (rpm)	51.62	52.14	1.01

Abbreviations : QUA Quadriceps; HAM Hamstrings

Acknowledgments: FAP-DF and CNPQ.

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Feasibility and Initial Efficacy of Smartphone-based Exercise Training After Stroke (SETS) Integrated with Functional Electrical Stimulation

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Introduction: Over 75% of Americans who experience a stroke are older adults (≥65 years) and exhibit long-term motor impairments (e.g., balance and gait dysfunctions)[1,2]. Combining clinical exercise training with supplemental agents like Functional Electrical Stimulation (FES) is known to improve mobility and gait performance post-stroke[3]. However, most older adults with stroke (OAwS) don't receive regular clinical interventions possibly due to healthcare (e.g., insurance coverage) or personal barriers (e.g., travel costs, caregiver bruden). Thus, we designed "Smartphone-based Exercise Training after Stroke" (SETS) with integrated FES delivered via a smart app for home-based setting.

Method: We examined the feasibility and initial efficacy of the SETS integrated with FES in OAwS with moderate-to-high imapirment (Chedoke McMaster Assessment ≤4/7). Thirty participants completed a 6-week exercise intervention in either a clinic-based (n=16) or home-based setting (n=14). The program included multicomponent exercises with FES. Feasibility was assessed through safety, adherence, and participant motivation. Initial efficacy was evaluated by comparing standardized measures of functional mobility, balance, strength and gait speed between the two groups.

Results: *Feasibility results* showed no adverse events (serious or non-serious) and showed high adherence (84.17±11.24%) among the home-based SETS with FES group. Further, the home-based group showed up to 40% improvement in patient-centered measures of motivation, acceptability and attitude, and system usability from the first to last week of training. *Initial efficacy* results showed comparable pre-to-post training improvements in all clinical outcomes amoong the two groups. Specifically, with no group differences at baseline and post-training, groups showed significant improvements in all clinical measures pre-to-post training ($p<0.05$). Improvements in most outcomes exceed the Minimal clinically independent differences (MCIDs) except for the Mini-BESTest.

Discussion and conclusion: Smartphone-based Exercise Training after Stroke (SETS), an intervention that integrates technology and functional electrical stimulation to deliver task-specific exercises, is a feasible paradigm for home-based training among OAwS, especially for those with moderate-to-high motor impairment. With the validation from future studies with larger samples, Smartphone technology-delivered exercise training with functional electrical stimulation can potentially help bridge the healthcare gap for those unable to access conventional, clinic-based physical therapy due to mobility, economic or logistic constraints

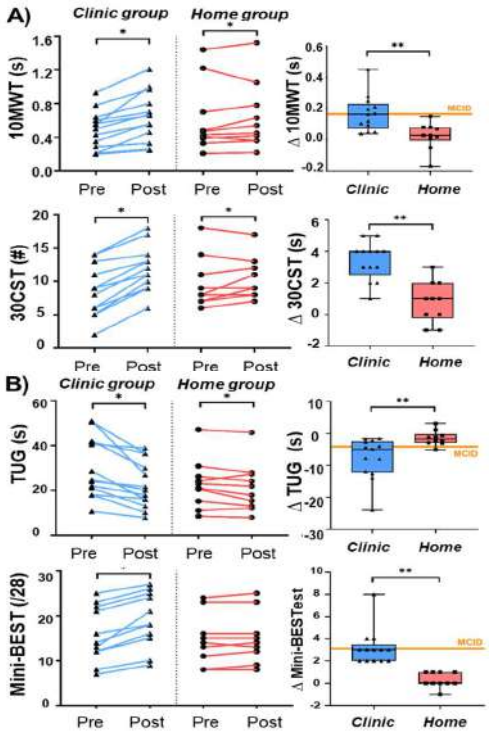


Figure 1: Clinical outcome measures assessed before and after training among home and clinic-based SETS with FES groups

Table 1
DEMOGRAPHICS AND BASELINE CHARACTERISTICS

Variables	Home group *(n=14)* Means (SD)	Clinic Group *(n=16)* Means (SD)
Age, years	72.5 (5.3)	78.5 (9.6)
Sex, male/female	8/6	10/6
Height, meter	1.7 (0.1)	1.8 (0.4)
Weight, kilogram	80.7 (16.6)	88.8 (28.6)
Chronicity, year	9.2 (2.9)	4.8 (5.8)
Hemi-side, Right/Left	6/8	6/10
Haemmorhagic/Ischemic	10/4	7/9

Funding: Midwest Roybal Center for Health Promotion and Translation as a doctoral pilot grant (Purohit) and ICR funds (Bhatt).

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ARTIFICIAL VISION FOR CLOSED-LOOP FES SYSTEMS AIMED AT ASSISTANCE AND REHABILITATION OF FOOT DROP

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Introduction: In order to replicate or assist the central nervous system, FES systems implement control strategies, and to make the system more robust by adjusting the stimulation parameters, closed-loop strategies are implemented. Feedback sensors are a critical part of any closed-loop FES system for gait rehabilitation. In our previous research [1], we noted that the angle of target joints was of particular interest in the articles we analyzed in the context of implementing a closed-loop FES system. Non-wearable vision-based technologies using standard or depth cameras are increasingly being used to track human motion. The ability of these cameras to extract the detailed information necessary for biomechanical analysis has recently been reported. In addition, a sequence of images can be used to estimate the speed at which objects are moving. These features could reduce costs, making non-wearable, marker-less tools more cost-effective than traditional gold standard technologies in everyday FES system evaluations.
Methods: Google's MediaPipe software was used to track body landmarks. It detects points of interest on the face and body joints with a convolutional neural network based on MobileNetV2 [2]. The angles between lines passing through each pair of joints were calculated using the identified points of interest. To evaluate the precision of the algorithm, assessments of upper limb (elbow) joint were conducted on videos of healthy patients, wherein the points of interest were identified and an angle was measured between three points. Subsequently, the outcome measures were verified with the assistance of a goniometer. Once the accuracy of the algorithm had been verified, it was sought to implement it in a process involving the use of an FES system in a patient with foot drop syndrome. The pose landmarker model tracks 33 body landmark locations and assigns a number to each one. Three points were selected, corresponding to landmarks of interest in the left (stimulated) leg (Figure 1). The patient completed a total of 10 laps. From 132 frames of the gait test, the visibility score of each landmark was calculated.
Results: To assess the precision of the algorithm in elbow joint assessment, the maximum percentage of error was found to be 5.18% (Table 1) Regarding the gait video, the average visibility scores were 0.7971, 0.8511 and 0.8664 for the knee, heel and toe landmarks.
Discussion and conclusion: Machine vision techniques can track points of interest, such as limb speed, angle, and acceleration. This methodology has potential for use in controlled rehabilitation settings. In previous works [2], the authors have developed embedded controllers for a gait-assistance FES system based on a finite state machine.This approach is capable of generating muscle activation patterns for the tibialis anterior and gastrocnemius muscles based on the detection of gait events using force or inertial sensors. Further work will include the comparison of the values measured by the proposed algorithm with the values obtained with the VICON system, as well as the implementation of the complete control system.

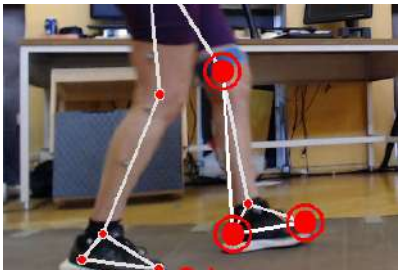


Figure **1**: Landmarks of interest in the left (stimulated) leg.

Table 1: Precision of the algorithm

True angle (°)	Estimated angle (°)	Absolute percentage error
Title	184.32	0.36%
208	214.21	2.98%
228	237	3.96%
255	266.68	4.58%
300	301.187	0.39%

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Understanding and Supporting Participants and Loved Ones: A Clinical Trial Testing a Novel Device to Restore Visual Perception

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Introduction: Participation in clinical trials has been shown to impact quality of life and cause distress both to the participant and their loved ones [1]. Emotional, physical, financial, and psychosocial burdens have all been reported [2]. Burden to clinical trial participants and loved ones has been shown to negatively impact clinical trial engagement, study compliance, and attrition [2,3]. The current clinical trial of a novel device to restore visual perception in individuals with visual impairment (NCT04634383) seeks to provide support to clinical trial participants and their loved ones in order to facilitate continued understanding of the trial, maintain true informed consent and study compliance, minimize attrition, and include participants as study team members. The current trial also sought to better understand the unique experiences of the loved ones of clinical trial participants.

Methods: Once enrolled in the study, participants and their loved ones attend monthly support group meetings with the psychology team. This support group was developed to allow participants to share their experiences with other participants, gather ongoing study information, and process their thoughts regarding study protocol. The support group is comprised of three clinical trial participants (two implanted) and their three caregivers (N=6). Members of the support group provide qualitative information of their experiences during the clinical trial. Additionally, loved ones of participants are offered the opportunity to participate in a separate, qualitative study. The separate study of one caregiver of a clinical trial participant included a demographic questionnaire and semi-structured individual interview aimed at better understanding the experiences of loved ones of clinical trial participants.

Results: The support group provided by the current clinical trial has allowed prospective participants the ability to decide whether or not to proceed in the trial. This support group has afforded participants implanted with the novel device the opportunity to continue to learn about the trial as well as provide their opinions and suggest changes of study assessments. Additionally, they provided the opportunity for loved ones to express their experiences and stay abreast of clinical trial protocols. The separate study of a loved one's experiences demonstrated both negative and positive experiences of clinical trial participation, some of which were unexpected (Fig.1). Negative experiences included changes in normal routine, employment, finances, and interpersonal relationships. Loved ones reported unexpected positive experiences as well including changes in relationships that were facilitated by participating in the support group.

Discussion and Conclusion: The support group for participants and qualitative study of loved ones have provided invaluable insight into the experiences, quality of life, and needs of participants and their loved ones during the current clinical trial. Learning about these experiences allowed study team members to better understand how to support them in an effort to maintain study engagement. Including a support group in clinical trials for participants and their loved ones is a beneficial addition to a clinical trial protocol.

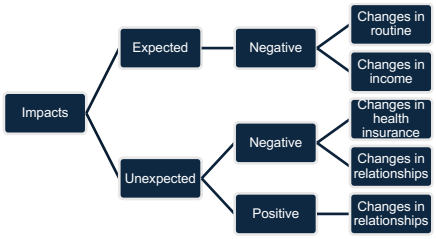


Figure 1: Results of Qualitative Interviews

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FEASIBILITY AND TOLERABILITY OF OPERANT CONDITIONING OF THE TRICEPS SURAE CUTANEOUS REFLEX IN INDIVIDUALS WITH CHRONIC INCOMPLETE SPINAL CORD INJURY

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Introduction: Operant conditioning of a stimulus-triggered EMG response can induce targeted plasticity in the pathway that produces the response [1]. This makes this approach a potential non-invasive, non-pharmacological therapeutic tool to guide beneficial plasticity in targeted neural pathways. Neuropathic pain (NP) and spasticity are common (both ≈70%) in individuals with chronic spinal cord injury (SCI) [2, 3]. Reduced excitability of non-nociceptive cutaneous reflexes (CRs) [4] and enhanced nociceptive pain processing [5] in the spinal cord—i.e., an imbalance between mutually suppressive nociceptive and non-nociceptive pathways [6] may play a role in abnormal pain experience and/or spasticity after SCI. To assess the feasibility and tolerability of operantly up-conditioning a non-noxious CR to alter abnormal spinal somatosensory processing, we are currently investigating operant up-conditioning of the triceps surae CR in individuals with chronic incomplete SCI.

Methods: 61-year-old male (10-years post C3-7 SCI with spasticity, P1) and 52-year-old male (3-years post C1-4 SCI with spasticity and NP, P2) have been studied with operant up-conditioning (Fig. 1). The soleus (P1) or medial gastrocnemius (P2) medium latency reflexes (MLRs) were operantly up-conditioned ***in the clinically more spastic (P1) or severe neuropathic pain leg (P2)***. The protocol consisted of 6 baseline and 30 up-conditioning sessions over 12 weeks. In each session, a 5x1-ms pulse (at 200 Hz) train of sural nerve (SRn) stimulation at a non-noxious level ≈0.95xPainThreshold (PainT) elicited MLRs (measured around 100 ms post stimulus onset). In all sessions, 225 reflex trials were administered while the participant stood, maintaining their natural standing level of EMG activity. The same investigator performed all experimental sessions. During baseline sessions, MLRs were simply measured. During conditioning trials of the conditioning sessions, the participant was encouraged to increase the MLR size and was given immediate feedback on whether it was larger than a criterion. Perceptual (PerT) and pain thresholds (PainT) were determined at the beginning of each session. MLR size, PerT, and PainT were compared between the 6 baseline and the final 6 conditioning sessions.

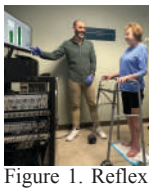


Figure 1. Reflex Conditioning

Results: In P1 [7] who completed 6 baseline and 30 up-conditioning sessions, MLR size over the final 6 conditioning sessions (5.9μV, mean absolute amplitude) was 184±56% larger (P=0.002, paired t test) than that of the baseline (2.1μV). PerT did not differ (-10±10%, P=0.20), but PainT over the last 6 conditionings sessions was 55±10% higher than that of the baseline (P<0.001). P2 completed 6 baseline and 10 up-conditioning sessions.

Discussion and conclusion: Results from the completed participant (P1) suggests that this conditioning paradigm may be beneficial in improving somatosensation. The protocol has been well-tolerated, and to date no side effects reported by participants. To understand the mechanisms and wider applicability of these early findings to others with chronic incomplete SCI, further studies and analyses are currently underway.

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Epidural Photobiomodulation to Preserve Tissue and Function Following SCI

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Introduction: Preserving the neural substrate and corresponding function to the extent possible following neural injury is critical. Much of the neural damage in spinal cord injury (SCI) is caused by an excessive inflammatory response after the initial insult[1,2]. Photobiomodulation (PBM) therapy, which consists of delivering specific doses and wavelengths of light to induce a biological response (presumably by facilitating cellular respiration, has shown great ability to reduce inflammation and oxidative stress, and to provide neuroprotection[3]. PBM therapy has been particularly effective when the appropriate light dosage is applied directly to target tissues, and successful examples of this include using PBM to slow age-related macular degeneration (AMD) (phase 3 clinical study)[4], and neuroprotective properties of PBM in a non-human primate model of Parkinson's disease (PD)[5] (a first-in-human study has been initiated[6]). Several groups have evaluated PBM in rat models of SCI, and the data are extremely encouraging (see Fig. 1). However, light was usually delivered transcutaneous in the rat, and this is not scalable to humans due to excessive intervening tissue that scatters and attenuates the light. Therefore, we propose to develop a percutaneous therapy that delivers the light from the epidural space immediately above the injury – which we term EpiPBM.

Methods: Initial investigations of EpiPBM will be in the rat, and a device appropriate for that animal model is currently under development in our lab. Key questions that will be investigated are: (1) Does EpiPBM yield benefit that is similar to transcutaneous methods[10]? (2) How does the effectiveness change with the initiation time of PBM therapy? (3) How does effectiveness change as a function of duration of PBM therapy (e.g., during the healing period)?

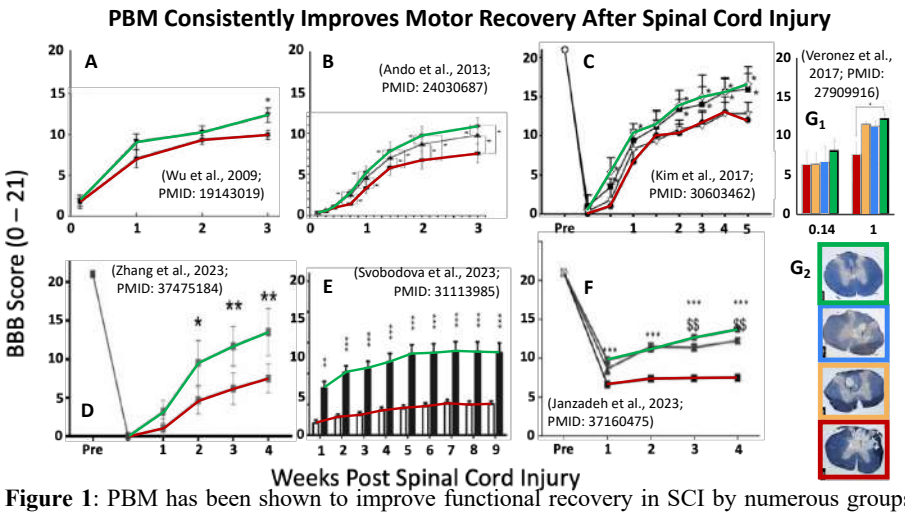


Figure 1: PBM has been shown to improve functional recovery in SCI by numerous groups around the world. Data from A-G (refs 9-15) show improvement with PBM (green) or without (red), and each data set is from a distinct group. G1 shows the data from increasing doses of light and G2 shows the effect of these doses on size of the injury cavity in a rodent model.

Results: The purpose of this abstract is to introduce the concept of EpiPBM. The team is currently designing the rodent EpiPBM device, and initial results will be shared.

Discussion and conclusion: Given the great effectiveness of PBM in rodent models of SCI, and to slow neurodegeneration in primates, EpiPBM for the treatment of SCI merits strong consideration. Our lab and at least two others[7,8] are engaged in research activities.

Acknowledgments: Consultant William Orinski contributes significantly to the design of the rodent EpiPBM device.

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THE UTILITY OF SCALP EEG IN CORTICAL VISUAL PROTHESIS TESTING

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Introduction: The Intracortical Visual Prosthesis (ICVP) delivers targeted electrical stimulation to the visual cortex to elicit phosphenes, aiming to provide artificial vision in individuals who are blind [1]. Scalp EEG offers real-time insight into the electrical physiology of the brain and allows for the early identification of epileptogenic patterns. This study investigates the utility of scalp EEG in two ICVP users during direct cortical stimulation sessions.

Methods: Two participants were implanted with wireless floating microelectrode arrays (WFMAs): the first received 25 arrays (400 electrodes), the second received 32 arrays (512 electrodes) implanted in the right lateral occipital hemisphere. These electrodes provide electrical stimulation directly to the visual cortex, modulating neural activity to elicit phosphenes and facilitate visual perception. Two-channel scalp EEG was monitored continuously (O_1, O_2-F_z reference, C_z ground) during testing sessions and a 1-30 Hz bandpass filter to isolate relevant physiological signals with particular focus on identifying pathological EEG patterns was used.

Results: Continuous scalp EEG monitoring during visual prothesis testing captured a variety of electrophysiologic phenomena. In one instance, early detection of a focal seizure through EEG allowed for timely intervention in response to impending epileptic activity, evident in the EEG signal and power spectra (Fig. 1). Normal event-related potentials in response to stimulation were observed in the EEG, similar to transient, steady-state visually evoked potentials from sighted individuals, reinforcing the role of neurostimulation in modulating cortical activity for vision restoration.

Discussion and conclusion: Scalp EEG is a valuable tool for neuroprosthetic development, ensuring real-time monitoring during cortical stimulation for early seizure detection. During testing conditions involving simultaneous activation of multiple intracortical electrodes, stimulation intensities exceeding thresholds, or prolonged stimulation durations, the risk of seizures increases, emphasizing the critical role of EEG monitoring for safety assessment.

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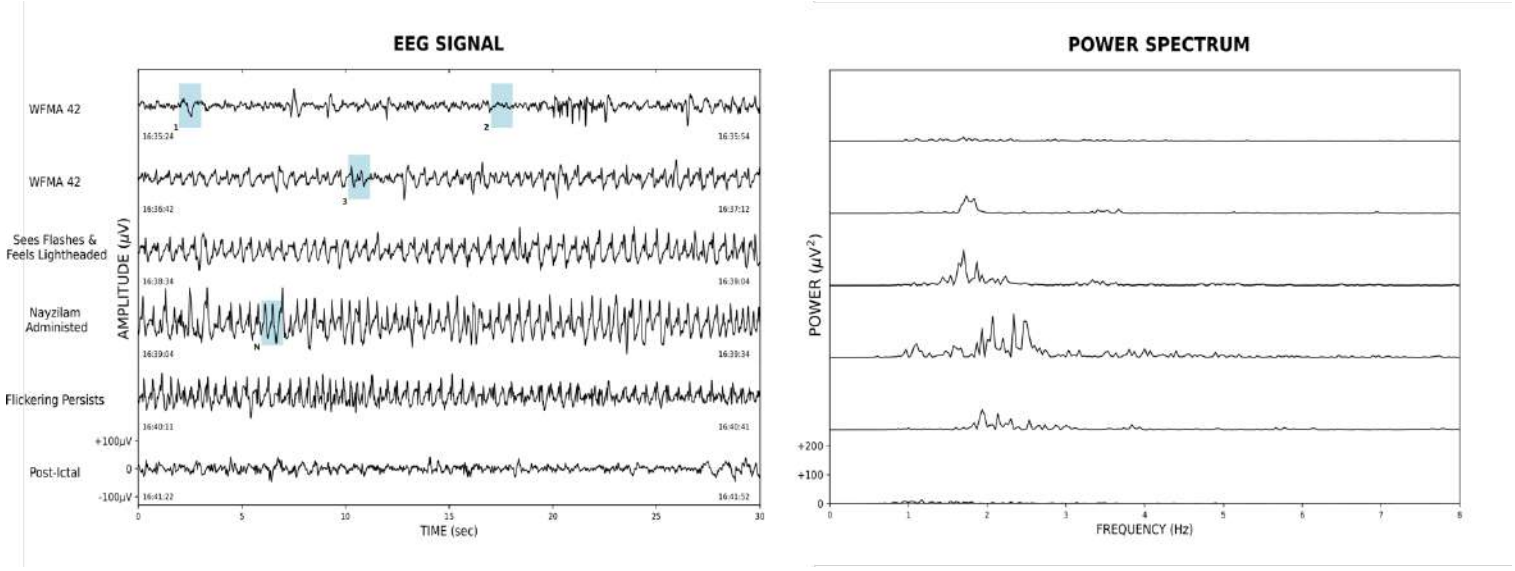


Figure 1: (a) 30 sec segments of the EEG showing the evolution of the seizure. Blue boxes indicate the 1 sec duration stimuli and how many times each was presented. Box (N) indicates the administration of the anti-seizure medication. (b) Fourier transform demonstrates power spectra of the EEG signal, highlighting when the seizure was resolving, returning to a post-ictal state.

Camera Assessment of an Intracortical Visual Prosthesis for Detecting Occupied and Vacant Chairs

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Introduction: Individuals who are blind often encounter adversities when performing daily visual tasks, such as navigating the environment and interacting with people and objects independently. Prosthetic devices, such as the intracortical visual prosthesis (ICVP), have emerged as promising technology for people who are blind, as they restore some basic visual function. The ICVP consists of wireless microelectrode arrays (WFMAs) that directly stimulate the visual cortex to produce visual percepts. Typically, a head-mounted external camera captures patterns of light that are converted to stimulation patterns to produce visual percepts. However, an alternate camera modality may be more suitable for specific tasks. This study evaluates an ICVP user's ability to identify occupied and vacant chairs using different camera modalities.

Methods: Twenty-five WFMAs were implanted into the right dorsolateral visual cortex of a 53-year-old participant who is blind. The participant performed two types of tasks - identifying occupied and vacant chairs- under three different camera conditions: 1) visible-light camera, 2) infrared thermal camera, and 3) all cameras off. Three white chairs were positioned against a dark background 40 cm apart and 2.4 m in front of the participant. Two chairs were left vacant for the occupied chair task and the participant was instructed to identify the occupied chair. For the vacant task, the participant was instructed to identify the one vacant chair. For both tasks there were 20 trials per camera condition. Accuracy and response time (RT) were recorded.

Results: For both camera modalities, accuracy rates were 95% for the occupied task. Performance was significantly faster with the infrared (mean RT=6.26 s) than visible-light (mean RT= 8.85 s) ($p < 0.05$) camera. When the prosthesis input was off, the accuracy rate was 25% (mean RT=2.12 s). A Kruskal-Wallis test revealed a significant difference between conditions ($\chi2(2) = 31.64$, $p <0.001$), with a post-hoc analysis showing significantly better performance with both cameras versus no input, but no difference between cameras. For the vacant chair task, accuracy rates were 95% for both visible-light (mean RT=6.81s) and infrared (mean RT=6.60 s) and 20% with the prosthesis input off (mean RT=1.49 s). A Kruskal-Wallis analysis found a significant difference in performance ($\chi2(2) = 35.12$, $p < .001$), with post-hoc results showing significantly better performance with both cameras versus no input, but no differences between cameras. There were no significant differences in RTs between cameras.

Discussion and Conclusion: Both camera modalities demonstrated accurate detection of occupied and vacant chairs. The infrared camera facilitated faster identification of occupied seats. Eliminating camera input led to significantly poorer performance, but faster responses due to guessing. Identifying occupied and available spaces is vital for promoting independent

navigation. Additional testing with a larger participant pool is necessary to further understand the capabilities of different camera modalities for more complex tasks.

Neural Network-Based Torque Estimation of FES-Activated Quadriceps Using Novel Sparse Wearable Ultrasound Sensors

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Introduction: Hybrid devices combine powered actuation and functional electrical stimulation (FES) for gait rehabilitation in spinal cord injury and stroke populations, but FES-induced fatigue limits their functionality. Ultrasound (US) techniques are viably shown to provide limited fatigue feedback for hybrid exoskeleton controllers [1], but conventional US probes are non-body conforming and cannot effectively capture muscle states during dynamic motion (ex. swing phase of walking). In this work, we address these limitations using sparse wearable ultrasound sensors (WUS) [2] to estimate knee torque generated during isometric and isokinetic FES-driven seated knee extensions. Deep learning models constructed from WUS A-mode data allow us to efficiently observe muscle states.

Methods: Three able-bodied subjects completed two isometric and two isokinetic trials for this study. The experimental setup is shown in **Fig. 1a**, with each subject seated at a dynamometer and electrodes and a 2x4-element sparse WUS placed on their left leg's vastus lateralis (VL) and vastus medialis (VM). For isometric trials, continuous FES (30 mA, 40 Hz) was applied to the VL and VM for two min as the leg was held at 75°. For isokinetic trials, FES was applied in 4 sec cycles (50% duty, 30 mA, 40 Hz) to the VL and VM for two min with the leg unconstrained. A-mode data from each WUS (100 Hz sampling) and dynamometer data was used to fit (80% training) subject-specific 2-layer neural networks (NN) for each contraction type. Models were applied to estimate torques based on input WUS data for evaluation.

Results: Of the various NNs tested, the 8-neuron layer size resulted in torque estimations that decently captured trends in the true torque data. We found an average correlation (R-value) of 0.89 for the model itself, and an RMSE of 4.4 Nm for the isometric trials. The isokinetic trials yielded lower values, with an avg. R-value of 0.47 and an RMSE of 4.2 Nm.

Discussion and Conclusion: The performance difference between isometric and isokinetic trials was expected, as muscles translate laterally and axially during unconstrained movement, and it is difficult to image the same region of interest throughout. The sparse WUS observes more muscle area than traditional US probes from the spread of transducer elements. That we saw the torque trends captured to such a degree during both isometric and isokinetic motion (**Fig. 1b**) without any extra neuron-tuning represents the first step to real-time wearable US-based torque (muscle fatigue) feedback. In this work, we've shown how 2x4 sparse WUS are used to estimate torque in the VL and VM with emphasis on capturing trends during FES-driven seated knee extensions. Next, we'll improve the applicability of our isokinetic torque models to improve performance and minimize the calibration data needed. We also will create torque models for people with spinal cord injury to use the WUS as feedback as they receive gait assistance via hybrid exoskeletons.

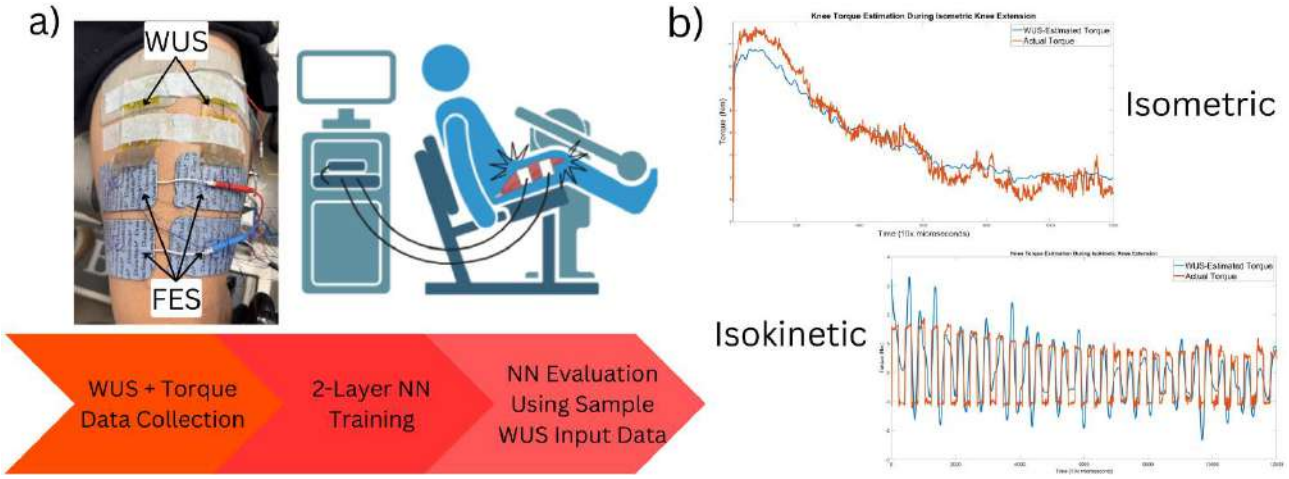


Figure 1: (a) Dynamometer Setup with FES & WUS Placements (b) Estimated Vs. True Torque Values for a Sample Isometric Trial and Isokinetic Trial

Acknowledgments: This work was supported by NSF Award# 2124017.

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Reconnecting the Hand and Arm to the Brain (ReHAB): Bi-directional FES+BMI System for Sensorimotor Functional Restoration

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Introduction: The Reconnecting the Hand and Arm to the Brain (ReHAB) Clinical Trial [1,2] aims to develop bidirectional brain-controlled neuroprostheses to restore motor and somatosensory function to individuals living with tetraplegia due to high cervical spinal cord injury (SCI). A chronically implanted multi-array brain-machine interface (BMI) allows for decoding of cortical activity into movement command signals for a chronically implanted Functional Electrical Stimulation (FES) system to reanimate hand and arm movements. Intracortical microstimulation (ICMS) of somatosensory areas, through the chronically implanted microelectrode arrays allows for restoration of sensation of touch to be used for feedback of grasp contact and force.

Methods: Study participant RP1 (27 years old, AIS-B, motor complete, sensory-incomplete C3-C4) was implanted with six intracortical microelectrode arrays (Blackrock Microsystems, Salt Lake City, UT) in primary motor (M1x2), primary sensory (S1x2), inferior frontal gyrus (IFGx1), and anterior intraparietal (AIPx1) cortical areas. He also was implanted with eight 16-channel composite flat interface nerve electrode (C-FINE) cuffs around major nerves of the upper arm. Recruitment curves were collected based upon each muscle's twitch response to single-contact stimulation to determine the activation profile of each FES C-FINE cuff. The study participant completed open- (observation only) and closed-loop (user-in-the-loop) virtual tasks to match grasp states and/or coordinated finger movements to that of a target hand. For closed-loop movements, a standard linear decoder mapped spike threshold crossings and high frequency spike power to grasp state or continuous joint velocities of the thumb and index fingers. We analyzed the modulation of neural features and the contribution to decoding grasp state for each array in the grasp network (AIP/IFG/M1). The participant ultimately was evaluated on his ability to complete a series of functionally relevant tasks through cortical controlled modulation of his implanted FES system.

Results: Microstimulation of electrodes in somatosensory cortex produced repeatable sensory percepts of individual fingers for restoration of touch sensation. Selective electrical activation of peripheral nerves produced antigravity muscle contractions, resulting in functional movements that the participant was able to command under brain-control to perform virtual and actual arm and hand movements. Independent contacts on each C-FINE had unique activation profiles (recruitment curve and order of recruitment). The study participant was able to use his combined BMI+FES system to perform self-selected functional tasks, such as object transfer, self-feeding, and hand-shaking.

Discussion and conclusion:. Overall the system was well tolerated and restored basic level of functionality to the individual with C3-C4 SCI. While the nerve cuff electrodes were less selective than hypothesized, each unique activation profile allowed for selective combinations to produce desired movements. Cortical signals showed strong modulation to various movements, and hence the system represent a viable approach for restoring brain-control of reach-to-grasp movements to individuals with chronic tetraplegia.

Acknowledgments: Funding: DoD SCIRP SC180308, VAMR 5I01RX002654

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Koopman-Based Model Predictive Control for Ankle Dorsiflexion and Plantarflexion Assistance via FES

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Introduction: We developed a novel, real-time, data-driven Model Predictive Control (MPC) framework for gait rehabilitation in individuals with paretic gait. Unlike existing approaches, our method uniquely integrates functional electrical stimulation (FES) of both ankle dorsiflexor and plantarflexor muscle groups to address the complete gait cycle. This is the first application of a Koopman operator framework in this context, enabling nonlinear ankle motion dynamics in a complete gait cycle to be captured through an infinite-dimensional linear operator. By leveraging this framework, we reformulate the MPC optimization problem as a computationally efficient quadratic program, making it feasible for real-time implementation.

Kinematic measurements, obtained through inertial measurement units (IMUs), are used to estimate foot pitch rates, providing state measurements for constructing an approximate linear predictor. Our methodology inherently incorporates the implicit dynamics of muscle actuation, including individual-specific activation and fatigue levels. This novel design enables a personalized relationship between FES input parameters and ankle motion, ensuring effective stimulation of the Tibialis Anterior (TA) muscle during the swing phase for ankle dorsiflexion and the gastrocnemius (GAS) muscle group during the stance phase for plantarflexion.

Simulation and experimental results from a subject with Multiple Sclerosis (MS) and three able-bodied subjects demonstrate the effectiveness of the proposed MPC scheme across multiple gait cycles. For the experimental task, one subject with MS (S01, age: 66 years, height: 153 cm, weight: 51 kg) with impaired volitional control of the left leg and three able-bodied subjects [A1, A2, A3, age: 26, height: 172cm, weight:78 kg] completed a gait rehabilitation protocol using the system. The MPC problem was formulated as a trajectory tracking problem, ensuring sufficient foot clearance during the swing phase and effective push-off during the stance phase. Compared to pre-FES performance, the intervention facilitated greater stability, improved toe clearance, and normalized ankle motion dynamics across multiple gait cycles.

Discussion and Conclusion:

This study presents the real-time application of a Koopman operator-based data-driven MPC framework for ankle assistance for complete gait cycle via FES. By directly leveraging kinematic measurements and eliminating the need for prior system identification, our approach sets a new benchmark for personalized and adaptive gait rehabilitation. Future work aims to integrate real-time surface electromyography and ultrasound-based muscle activation estimates to enhance the controller's adaptability and closed-loop performance. This integration will further solidify the data-driven relationship between muscle fatigue, activation dynamics, and FES input parameters, ensuring robust and optimal gait assistance.

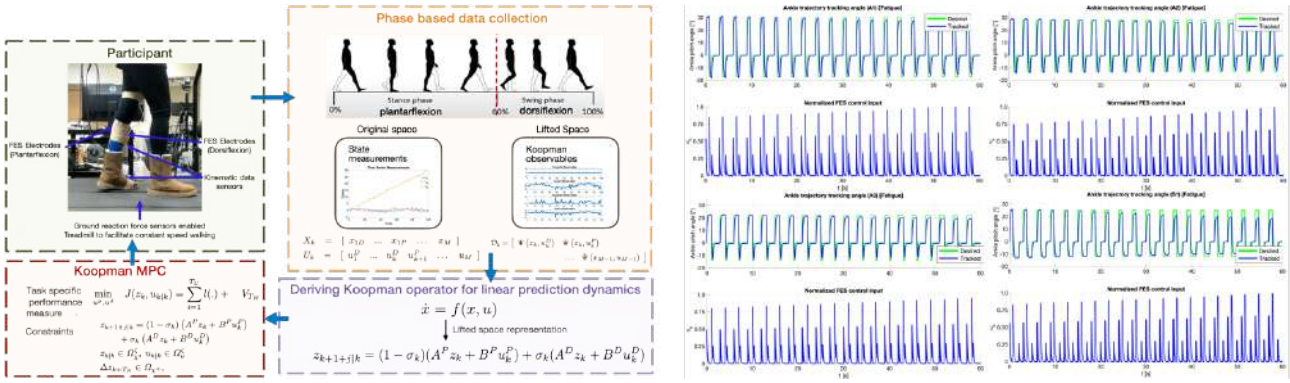


Figure 1: LEFT – Control architecture block diagram. RIGHT – Trajectory tracking results.

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Transcutaneous Spinal Cord Stimulation for Motor Facilitation During Cycling in Individuals with Spinal Cord Injury: A Proof-of-Concept Study

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Introduction: Transcutaneous Spinal Cord Stimulation (tSCS) is a non-invasive technique which has shown promising results in the neurorehabilitation of individuals with Spinal Cord Injury (SCI) [1]. This study investigated the impact of tSCS on motor facilitation during cycling in individuals with SCI. Cycling is well-suited for neurorehabilitation as it avoids the risk of falling and the weight-bearing challenges [2].
Methods: The study (No. 50/2023), approved by the Politecnico di Milano Ethical Committee, involved four participants with chronic motor complete SCI (AIS A or B). tSCS was applied through self-adhesive electrodes (Axelgaard Manufacturing Co. Ltd., USA) positioned at L1-L2 (anode) and T11-T12 (cathode) spinosus processes. EMG data from eight leg muscles (rectus femoris, biceps femoris, tibialis anterior and gastrocnemius of both sides) were recorded. The protocol consisted of three phases: Calibration, Passive Cycling (PC), and tSCS Cycling (CY). During Calibration, the motor threshold amplitude was determined using single tSCS pulses. Passive Cycling involved pedaling, on a motor-assisted trike (model 700, Catrike, US), without stimulation, while tSCS Cycling consisted of two 3-minute blocks of pedaling with continuous constant-amplitude current stimulation (tSCS-only), repeated for three different stimulation frequencies (20, 50, or 80 Hz) in a randomized order. In one of the two blocks, the subject was asked to add the voluntary intent of cycling (tSCS+vol). Average pedal force were calculated for each protocol phase. Participants were asked to rate their feelings of pain, burning, cramping, tingling and pressure on a scale from 0 to 10 for each stimulation frequency. Follow-up calls were conducted 24–48 hours later to record any stimulation-related changes they experienced.
Results: Two trials were conducted for participants 01, 02, and 03, while one trial was conducted for participant 04. Due to the participants' unique clinical histories and limited number of trials, all the data were analyzed separately. The results, consisting of EMG activity, force, and secondary effects, valid for tSCS-only and tSCS+vol, are summarized in Table 1.
Discussion and conclusion: The protocol was safe and well-tolerated, though motor improvements were modest, likely due to the short intervention duration. tSCS modulated muscle activation, sometimes amplifying or reducing it, and one participant showed enhanced pedaling force when combining stimulation with volitional effort. The stimulation reduced spasticity and led to reported side benefits, including decreased limb rigidity, improved bowel function, and regained bladder sensitivity. While promising, the findings are limited by the small sample and short trial period. Future research should explore longer protocols and their effects, also in combination with Functional Electrical Stimulation (FES).

Table 1: Effects of tSCS, in terms of effects on EMG, force, perception, and secondary outcomes, for the four recruited subjects.

	S01 – ASIA A, D4	**S02 – ASIA A, D3**	**S03 – ASIA B, D12**	**S04 – ASIA B, D2**
EMG (PC vs CY)	Amplification (50 Hz)/Reduction (80Hz) of the signal	Amplification (50 Hz)/Reduction (80Hz) of the signal	Amplification (50 Hz)/Reduction (80Hz) of the signal	Amplification (50 Hz)/Reduction (80Hz) of the signal
Force at the pedals (PC vs CY)	Small increase during the pulling phase	Small increase during the pulling phase	Increased active contribution	Increased active contribution especially for tSCS+vol
Perception	No discomfort	Tingling, heating	Mild discomfort	Low discomfort
Secondary Effects	None reported	Reduced spasticity, improved bladder/bowel sensitivity	Reduced spasticity, rigidity, improved bladder/bowel sensitivity	Reduced spasticity, rigidity, improved bladder/bowel sensitivity

Acknowledgments: This research was supported by INAIL (Istituto Nazionale per l'assicurazione contro gli Infortuni sul Lavoro, Italy), with PR19-RR-P5-FESleg project. We also thank Axelgaard Manufacturing Ltd for donating us the stimulation electrodes.

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Impact of burst nerve stimulation on spinal excitability in the upper limb

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Introduction: Transcutaneous electric nerve stimulation (TENS) is a common rehabilitation tool used to augment somatosensory input for improving motor recovery in stroke [1] and spinal cord injury [2]. It provides differential effects based on the frequency and intensity of TENS [3]. Recently, there has been a growing interest in burst TENS, where high-frequency carrier signal is demodulated into low-frequency bursts. This temporal-modulated TENS has been shown to induce similar effects (increased motor output) while overcoming the limitations (fatigue, parasthesia) of high-frequency TENS [4] [5]. However, the underlying mechanisms modulating motor output remain unclear. This study evaluated the impact of burst TENS on spinal excitability by quantifying F-wave and H-reflex characteristics in the upper limb.
Methods: Four healthy adults (mean age, 28 ± 6; 2 females) participated in the study. F-waves were elicited from the First Dorsal Interrosseous (FDI) by stimulating the ulnar nerve (200-µs pulse, 60 pulses at 1 Hz, 150% M-max), and measuring peak-to-peak amplitude and persistence (percentage of stimuli evoking a response). H-reflexes were evoked for the Flexor Carpi Radialis (FCR) muscles by stimulating the median nerve near the elbow, identified by latency (12 - 25 ms) and amplitude fluctuation with stimulus intensity F-wave and H-reflex assessments were performed before and after 40 mins of burst TENS or control (i.e., no stimulation). Burst TENS was applied to wrist nerves (median, radial, ulnar) via surface electrodes, in trains of 400 µs biphasic pulses at 100 Hz, demodulated at 5Hz (100 ms on/off). Stimulus intensity was adjusted to provide paresthesia without muscle contractions or discomfort.
Results: Fwave amplitude for the FDI muscle significantly increased (0.987 ± 0.10 for control vs 1.182 ± 0.11 for burst TENS; F = 6.16, p = 0.048) due to burst TENS compared to control condition. However, persistence did not differ between conditions (0.932 ± 0.12 for control vs 1.029 ± 0.07 for burst TENS; F = 2.14, p = 0.27). H-reflex amplitude for the FCR muscle also showed no significant difference (0.91 ± 0.48 for control vs 1.20 ± 0.35 for burst TENS; F = 0.95, p = 0.39).
Discussion and conclusion: Our results suggest spinal mechanisms contribute to increased motor output, particularly in muscles distal to the stimulation site. This aligns with previous findings of focal effects in the upper limb and increased thoracic evoked potentials [6] [7]. We speculate burst TENS enhances motor output through neuromodulatory inputs to spinal motoneurons. Further research with larger sample sizes is required to confirm these findings.

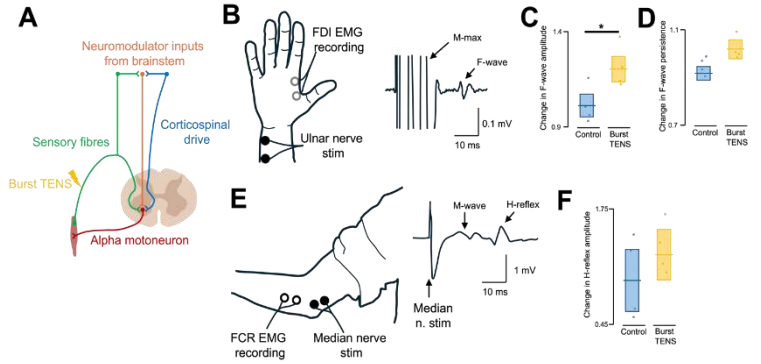


Fig 1:Modulation of spinal excitability in the upper limb due to burst TENS. A) Alpha motoneurons receive inputs from corticospinal, neuromodulatory, and sensory inputs. Burst TENS might modulate these pathways and increase motor output. Evaluating motoneuron excitability at the FDI (B-D) and FCR (E-F) show that F-wave amplitude increased due tob urst TENS (C). However, H-reflex amplitude was not modulated for the FCR due to burst TENS. Solid lines indicate mean and the bars represent standard deviation. * denotes p < 0.005.

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Effects of high frequency sacral nerve stimulation on lower urinary tract function in awake, healthy animals

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Introduction: Many individuals with spinal cord injury or other neurological disorders that affect lower urinary tract function require the use of a catheter to empty their bladder. Using a catheter is associated with risks of urethral trauma and urinary tract infection, and approaches that would eliminate the need for catheters are a high priority for these individuals. Reduction of urethral sphincter pressure may have the potential to promote bladder emptying without catheters. Peripheral nerve stimulation at frequencies of 500-10,000 Hz is associated with reduction of muscle contraction without causing muscle fatigue. We hypothesized that high frequency stimulation of the sacral roots, which include neurons that innervate the lower urinary tract, would be associated with reduced urethral pressures without also reducing bladder pressures.

Methods: We implanted five healthy cats with nerve cuff electrodes bilaterally on sacral roots S1 and S2, which were connected to wireless implantable pulse generators that also measured pelvic floor electromyogram (EMG). Pelvic floor EMG acted as a proxy measure for urethral sphincter activity. We also implanted the Urological Monitor of Conscious Activity (UroMOCA), which is a wireless bladder pressure and volume sensor. During sessions wherein the animals were awake and behaving, we applied stimulation at frequencies of 20 Hz, 500 Hz, or 10 kHz, and amplitudes up to the tolerance limits of each animal.

Results: The stimulation was tolerated well by the subjects. Stimulation at a frequency of 10 kHz was associated with a 19% reduction in EMG amplitude compared to stimulation at 20 Hz ($p << .001$), suggesting blockade of the nerves that control the pelvic floor muscles (Figure 1). Stimulation at 500 Hz appeared to also result in reduced EMG responses compared to 20 Hz, but this difference was not significant. Bladder pressures were sometimes increased at stimulation amplitudes near the tolerance limit, regardless of stimulation frequency.

Discussion and conclusion: These data indicate that high frequency sacral root stimulation has the potential to reduce pelvic floor activity and may also reduce urethral sphincter pressure in order to achieve catheter-free bladder emptying for individuals with neurologically-driven urethral sphincter overactivity.

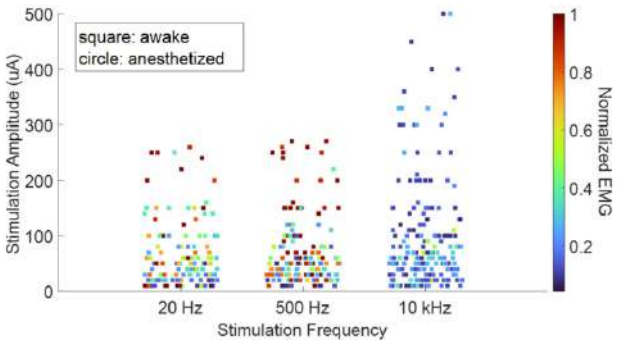


Figure **1**: Heat map showing intensity of pelvic floor EMG responses to stimulation frequency and amplitude.

Effects of 600 Hz sacral root stimulation on lower urinary tract function in an individual with spinal cord injury

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Introduction: Bladder dysfunction is an unmet challenge that is highly prioritized by individuals with spinal cord injury (SCI). Sacral anterior root stimulation (SARS) is effective in achieving bladder emptying for many individuals with SCI and difficulty emptying their bladder. However, individuals with reflex urethral sphincter contractions during bladder emptying require a rhizotomy, which is cutting the sensory nerves to stop the reflex urethral sphincter contractions. Cutting the sensory nerves yields downsides of inhibiting certain desirable reflexes, such as sexual, bowel, and loss of any remaining pelvic sensations. Stimulation at 600 Hz is believed to block synaptic transmission, which could be used to reduce urethral sphincter pressure and promote bladder emptying.
Methods: We enrolled n=3 study participants who were previously implanted with a SARS device. Participants 1 and 2 have had a rhizotomy, and participant 3 did not have a rhizotomy. We tested SARS at 600 Hz frequency to determine its effect on urethral sphincter and bladder function during a single session. We used clinically standard urodynamics and anorectal manometry methods to measure urethral pressure, anal sphincter pressure, bladder pressure, rectal pressure, and pelvic floor electromyogram (EMG) simultaneous with electrical stimulation of the sacral roots at 20 or 600 Hz.
Results: Frequency was a significant factor predicting the variance in the bladder, urethral, rectal, and anal pressure responses to sacral nerve stimulation ($p = 0.0002$, 0.0309, 0.0002, and 0.0018, respectively). Stimulation at 20 Hz evoked muscle contractions, as expected. However, at lower stimulation amplitudes, it resulted in decreased bladder pressure in Participant 3. Stimulation at 600 Hz showed a weak, variable effect of reduced pressures in all participants.
Discussion and conclusion: This case series presents a first-in-human proof-of-concept. While these data are promising, testing other higher stimulation frequencies and increasing our sample size are needed to evaluate a potential therapy for achieving catheter-free voiding.

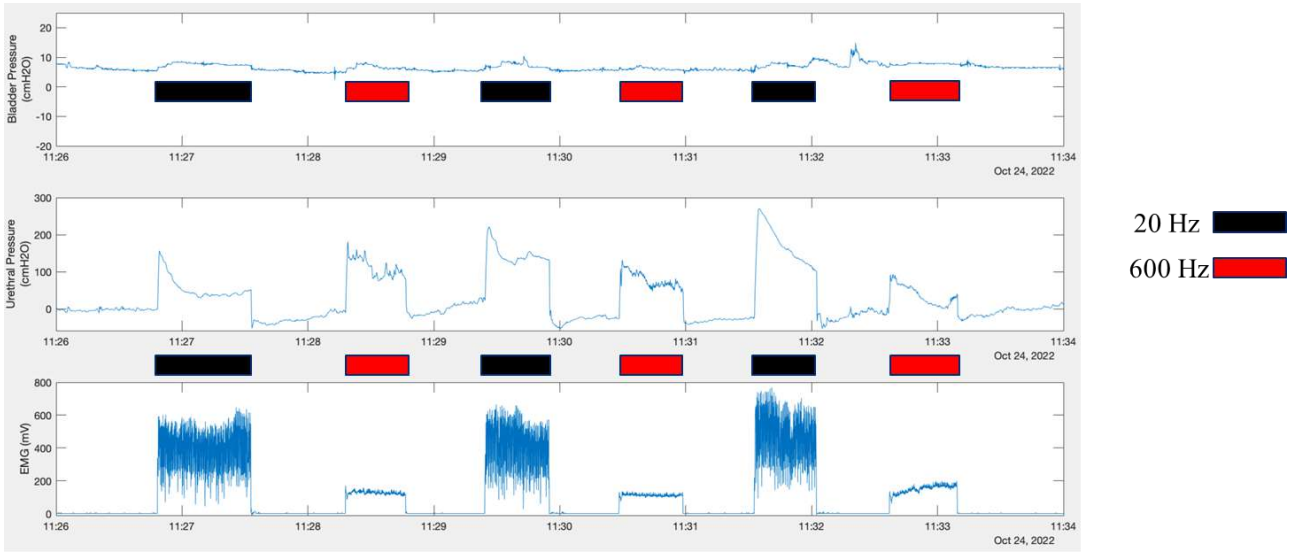


Figure **1**: Example responses of bladder pressure, urethral pressure, and pelvic floor electromyogram to sacral nerve stimulation at 20 Hz (black bar) or 600 Hz (red bar).

PROPRIOCEPTION TRAINING IN POST-STROKE SURVIVORS: A CHALLENGE FOR ELECTRICAL STIMULATION?

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A key clinical challenge includes the loss of proprioception in conditions like stroke and spinal cord injuries, impairing movement, and posture. Traditional rehabilitation often overlooks proprioception, even if the role of proprioceptive feedback in motor learning is crucial in improving functional outcomes as demonstrated by the scientific research. Functional Electrical Stimulation (FES), typically used to induce muscle contraction in order to reproduce a functional motor task, can act as augmented proprioception by providing artificial sensory feedback. This compensates for lost proprioception and improves movement awareness, though optimizing stimulation parameters is still a challenge. In particular, when coming to neurorehabilitation, individual approaches are needed due to varying deficits. Personalized FES is essential, involving the assessment of individual deficits and tailoring stimulation to target specific movements. The integration of FES with robotics may open the way to innovative strategies for proprioception training into neurological rehabilitation by offering precise, customizable stimuli that reinforce sensorimotor pathways, enhancing recovery. Combining FES with task-specific exercises strengthens sensorimotor learning, and AI-driven customization could further refine interventions by addressing key clinical challenges, highlighting recent evidence, and emphasizing personalized approaches to enhance motor control and recovery. Assistive devices like exoskeletons and prosthetics can incorporate proprioceptive feedback, improving user control. Adaptive strategies that adjust feedback based on proprioceptive loss help restore functionality. Further research is needed to provide insights on how FES, robotics, and assistive technologies can transform rehabilitation by addressing proprioceptive deficits and personalizing treatment for better outcomes.

Acknowledgments: This work was supported also by INAIL (Istituto Nazionale Assicurazione contro gli Infortuni sul Lavoro), within FeatherEXO project (PR23-RR-P1).

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