2021 10th International IEEE/EMBS Conference on Neural Engineering (NER)
Virtual Conference, May 4-6, 2021

Targeting post-stroke walking automaticity with a propulsion-augmenting soft robotic exosuit: toward a biomechanical and neurophysiological approach to assistance prescription*

Regina Sloutsky, Meryem A. Yücel, Ashley N. Collimore, El Ottman, Terry D. Ellis, Conor J. Walsh, David A. Boas, Louis N. Awad

Abstract— **Human locomotor control ranges on a spectrum of automaticity, from highly automatic strategies that require minimal cognitive input, to attention-demanding executive-control strategies. The neural circuitry that facilitates automaticity is impaired by stroke, resulting in a compensatory shift toward executive-control, as well as reduced paretic propulsion and increased step-to-step variability. We have developed a soft robotic exosuit to augment paretic propulsion by providing paretic plantarflexor assistance during the propulsive phase of walking. For this preliminary study, we hypothesized that changes in walking automaticity would accompany changes in paretic propulsion. When plantarflexor assistance timings were tuned to reduce propulsion variability—a biomechanical measure of automaticity—a -14.7±2.5% variability reduction was accompanied by increased paretic propulsion (%Δ:+6.4±6.3%) and prefrontal cortex activity (Δ oxygenated hemoglobin:+1.08E-04±1.05E-04 M mm). When plantarflexor assistance timings were instead tuned to reduce prefrontal cortex activity—a neurophysiological measure of automaticity—a -1.3E-05±1.1E-05 M mm decrease in oxygenated hemoglobin was accompanied by both increased paretic propulsion (%Δ:+4.4±8.1%) and reduced propulsion variability (%Δ:-3.7±19.3%). Biomechanical and neurophysiological measures of automaticity are sensitive to exosuit assistance timing changes, but are differentially affected, highlighting the need for individualized tuning.**

I. Introduction

Human locomotor control ranges on a spectrum of automaticity; highly automatic control strategies require minimal cognitive resources, while executive control strategies are attention-demanding. The neural circuitry that enables walking automaticity largely consists of cerebellum, brain stem, and spinal cord; in contrast, executive control depends heavily on cortical brain regions, and more specifically, the prefrontal cortex. Typical healthy adult walking employs automatic control strategies that allow for simultaneous performance of cognitively demanding tasks, such as talking or thinking; executive control strategies are used during learning and performing highly complex tasks.

Stroke often impairs the neural pathways that facilitate automatic control, and thus leads to a compensatory shift to executive control mechanisms, which manifests as increased recruitment of the prefrontal cortex—a recognized *neurophysiological* sign of reduced automaticity[1]. Moreover, whereas healthy automatic walking is characteristically symmetric and periodic, individuals post-stroke demonstrate asymmetric walking patterns[2,3] and increased stride-to-stride variability[4]—a recognized *biomechanical* sign of reduced automaticity[5]. Post-stroke changes in walking automaticity can thus be measured using both neurophysiological (i.e., prefrontal cortex activity) and biomechanical (i.e., stride-to-stride variability) approaches.

Impaired paretic limb forward propulsion is a common walking deficit observed post-stroke[2] that is associated with gait asymmetry[3] and variability[4]. Our group has developed a soft, wearable, robotic exosuit to address post-stroke propulsion deficits by mechanically augmenting stance phase paretic plantarflexion[6,7]. Unlike rigid exoskeletons or ankle foot orthoses that constrain users to pre-defined kinematic trajectories, soft robotic exosuits provide low-to-moderate levels of assistance to augment a user's movements. Moreover, exosuit assistance parameters can be rapidly tuned to address both inter-subject heterogeneity in gait impairments and intra-subject variability due to changes in walking context or experience-dependent processes (e.g., fatigue and learning).

Our previous work has shown that exosuits can improve propulsion symmetry by increasing paretic propulsion, with the propulsion improvement influenced by the prescribed onset timing of plantarflexor assistance. Individualized tuning of plantarflexor timing not only maximized propulsion benefits, but was necessary to avoid timings that reduced paretic propulsion and increased interlimb asymmetry[6]. In this study, we aimed to determine the effects of propulsion augmentation by a soft robotic exosuit on post-stroke walking automaticity—measured by both stride-to-stride propulsion variability and prefrontal cortex activity. A secondary aim was to determine if these different, but conceptually-linked metrics of walking automaticity are modified in the same way by different plantarflexor assistance timings.

II. Methods

A. Participants

Three subjects (S1, S2, S3) >6 months post-stroke completed this study (age: 46.9±10.4 years; chronicity: 8.2±5.1 years; speed: 1.1±0.4 m/s). Subjects provided written

*Research supported by the American Heart Association (18IPA34170487), the National Institute of Health (1UL1TR001430), and the National Science Foundation Research Traineeship Program (NRT): Understanding the Brain (UtB): Neurophotonics DGE-1633516.

R. Sloutsky, A.N. Collimore, E.M. Ottman, T.D. Ellis, and L.N. Awad are with the Department of Physical Therapy and Athletic Training, Boston University, Boston, MA 02215 USA (*Corresponding authors*: *R. Sloutsky* (reginas@bu.edu) and *L.N. Awad* (louawad@bu.edu).

M.A. Yucel and D.A. Boas are with the Department of Biomedical Engineering, Boston University, Boston, MA 02215 USA.

C.J. Walsh is with the John A. Paulson School of Engineering and Applied Science, Harvard University, Cambridge, MA 02138 USA.

informed consent for procedures approved by the IRB.

B. Experiment Overview

Participants completed three 10-min bouts of exosuit-assisted treadmill walking at a comfortable walking speed, with each bout separated by 10 minutes of rest. Each bout consisted of alternating periods of walking with and without plantarflexor assistance and tested one of three randomized plantarflexor onset timings: 10%, 50%, or 90% of paretic single limb support (SLS) (**Fig. 1a**). Prior to data collection, participants were provided a 1-min acclimation bout for each tested condition. For all bouts, the magnitude of plantarflexor force was set to 25% bodyweight[6,7] and the magnitude of dorsiflexor assistance was individualized to each user based on visual gait analysis by a physical therapist[6,7]. Although our objective was to evaluate the effects of different paretic plantarflexor assistance onset timings, paretic dorsiflexor assistance was provided during the paretic swing phase to ensure safe ground clearance. Because dorsiflexor assistance was held constant across all walking bouts, our results present the independent effects of tuning plantarflexor onset timing.

C. Soft Robotic Exosuit

The soft wearable robotic exosuit (ReStore, ReWalk Robotics Inc., Marlborough, MA) (**Fig. 1b)** uses cables to mechanically augment paretic dorsiflexion and plantarflexion during the swing and stance phases of gait, respectively[7,10]. A focal attribute of this technology is the ability to modulate assistance profiles, including the assistance onset timing. Assistance timing is commanded as a function of the gait cycle, with bilateral gait events determined using inertial measurement units. Additional details regarding the design and assistive algorithms can be found in previous work[7,10].

D. Data Collection, Processing, and Analyses

Paretic Propulsion and Automaticity: The anteriorly-directed ground reaction force generated by the paretic limb from propulsion onset to toe-off was measured during the 10-min walking bouts using an instrumented treadmill (Bertec Corp., Columbus, OH). Ground reaction force data were collected at 1,000-Hz and filtered using a fourth order Butterworth filter at 7-Hz. The propulsive impulse for each paretic step was used to measure propulsion magnitude (**Fig. 1b**). Stride-to-stride propulsion impulse variability[3] was computed as the coefficient of variation (standard deviation/mean*100) across paretic steps to measure propulsion variability and characterize biomechanical automaticity. For both propulsion magnitude and variability, differences between each plantarflexor assistance period and the preceding period without plantarflexor assistance were computed per trial and averaged across the three trials per bout. That is, the effect of each plantarflexor assistance onset timing is measured as the average change across the three trials tested for each onset timing. To focus the analysis on steady state walking, we analyzed the final 15 steps from each period.

Prefrontal Cortex Activity and Automaticity: To characterize neurophysiological automaticity, changes in oxygenated hemoglobin in the prefrontal cortex were measured using continuous-wave functional near-infrared spectroscopy (fNIRS; CW6-NIRS, TechEn Inc., Milford, MA) with two different wavelengths of 690 and 830 nm. To target bilateral prefrontal cortices (Brodmann Area 10)[8], we used AtlasViewer software to design a customized probe, with 4 light sources, 8 long-separation detectors, 2 short-separation detectors and a total of 10 source-detector channels with an inter-optode distance of 3.0 cm. Raw optical data were converted first into optical density and then into concentration changes, without pathlength correction, using HomER3[9] software executed using MATLAB (v R2019b, Mathworks Inc., Natick, MA). Short-separation channel measurements were used to regress out the contamination from superficial layers in the long-separation channel measurements using a General Linear Model approach. To compute walking automaticity from a neurophysiological perspective, changes in prefrontal cortex activity were measured as the relative change in oxygenated hemoglobin between the final 5 seconds of each period without plantarflexor assistance and 50 seconds of the subsequent period with plantarflexor assistance, with the first 5 seconds after a transition excluded to allow for cerebral blood flow to stabilize. Data were averaged across the three trials for each of the plantarflexor assistance onset timings.

Analyses: Descriptive statistics (average±SD) are reported for group and individual data within and across conditions.

III. Results

A. Group data

Tuning based on paretic propulsion magnitude: Individualizing plantarflexor assistance onset timings to

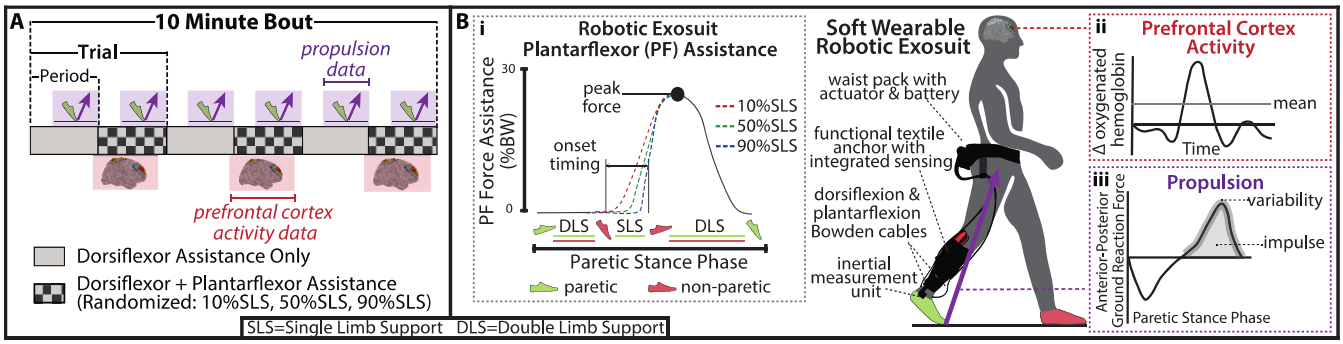

Figure 1. Methods: A. Participants completed three 10-min bouts (one shown). Each bout consisted of three repeated trials. Each trial consisting of two periods. In the first period, only dorsiflexor assistance was provided. In the second, both dorsiflexor and plantarflexor assistance were provided. The onset timing of plantarflexor assistance was randomized across bouts. Paretic propulsion and prefrontal cortex activity data were collected in each period as shown. **B**. Soft robotic exosuit components. **i**. Plantarflexor assistance onset timing was tested at 10%, 50%, and 90% of paretic single limb support (SLS). Plantarflexor assistance peak force was set to 25% bodyweight (%BW). **ii**. Prefrontal cortex activity was measured as the change in oxygenated hemoglobin concentration. **iii**. Paretic propulsion magnitude and variability (i.e., coefficient of variation) were computed from the impulse of the anterior ground reaction force.

increase the magnitude of paretic propulsion impulse resulted in improved propulsion magnitude (%Δ: +9.6±4.9%), reduced propulsion variability (%Δ: -12.2±4.6%), and increased prefrontal cortex activity (Δ oxygenated hemoglobin: +8.2E-05±11.8E-05 M mm) (**Fig. 2**).

Tuning based on paretic propulsion variability: Individualizing plantarflexor assistance onset timings to maximize the reduction in paretic propulsion variability resulted in increased paretic propulsion magnitude (%Δ: +6.4±6.3%), reduced paretic propulsion variability (%Δ:-14.7±2.5%), and increased prefrontal cortex activity (Δ oxygenated hemoglobin: +1.08E-04±1.05E-04 M mm).

Tuning based on prefrontal cortex activity: Individualizing plantarflexor assistance onset timings to maximize the reduction in prefrontal cortex activity resulted in increased paretic propulsion magnitude (%Δ: +4.4±8.1%), reduced paretic propulsion variability (%Δ: -3.7±19.3%), and reduced prefrontal cortex activity (Δ oxygenated hemoglobin: -1.3E-05±1.1E-05 M mm).

B. *Individual participant data*

S1—Paretic propulsion magnitude was most improved using a 50% SLS plantarflexor assistance onset timing (%Δ: +11.3%). This onset timing also resulted in improved paretic propulsion variability (%Δ: -7.7%) and reduced prefrontal cortex activity (Δ oxygenated hemoglobin: -0.23E-05 M mm), but was not the most effective timing for either of these metrics of automaticity. The largest improvement in propulsion variability was found using a 10% SLS plantarflexor assistance onset timing (%Δ: -15.4%) and the largest improvement in prefrontal cortex activity was found using a 90% SLS plantarflexor assistance onset timing (Δ oxygenated hemoglobin: -2.26E-05 M mm).

S2—Paretic propulsion magnitude was most improved using a 90% SLS plantarflexor assistance onset timing (%Δ: +4.1%). Selection of either the 10% SLS or 50% SLS plantarflexor assistance onset timing resulted in penalties to paretic propulsion magnitude (%Δ: -5.1% and -1.9%, respectively). The 90% SLS plantarflexor assistance onset timing also resulted in the greatest improvement in propulsion variability (%Δ: -12.0%), but a marked increase in prefrontal cortex activity (Δ oxygenated hemoglobin: +24.9E-05 M mm). Use of the 50% SLS plantarflexor assistance onset timing was most effective for reducing prefrontal cortex activity (Δ oxygenated hemoglobin: -1.45E-05 M mm).

S3—Paretic propulsion magnitude was most improved using a 10% SLS plantarflexor assistance onset timing (%Δ: +13.5%). Use of this timing was also most effective for both reducing propulsion variability (%Δ: -16.8%) and reducing prefrontal cortex activity (Δ oxygenated hemoglobin: -1.70E-06 M mm). In contrast, use of the 50% SLS plantarflexor assistance onset timing resulted in penalties across all outcomes, with reduced paretic propulsion magnitude (%Δ: -3.9%), increased paretic propulsion variability (%Δ: +29.7%), and increased prefrontal cortex activity (Δ oxygenated hemoglobin: +1.54E-05 M mm). Due to technical issues, S3 completed two conditions with two trials per bout.

IV. Discussion

Exosuit-induced increases in paretic propulsion magnitude were observed to be larger with the combined assistance of the paretic plantarflexors and dorsiflexors versus assistance of just the dorsiflexors. The magnitude of the increase in paretic propulsion was influenced by the onset timing of plantarflexor assistance. The major finding of this study was that walking automaticity was found to be similarly sensitive to the propulsion assistance provided by the soft robotic exosuit; however, the biomechanical and neurophysiological measurements of automaticity studied were differentially affected by each plantarflexor assistance

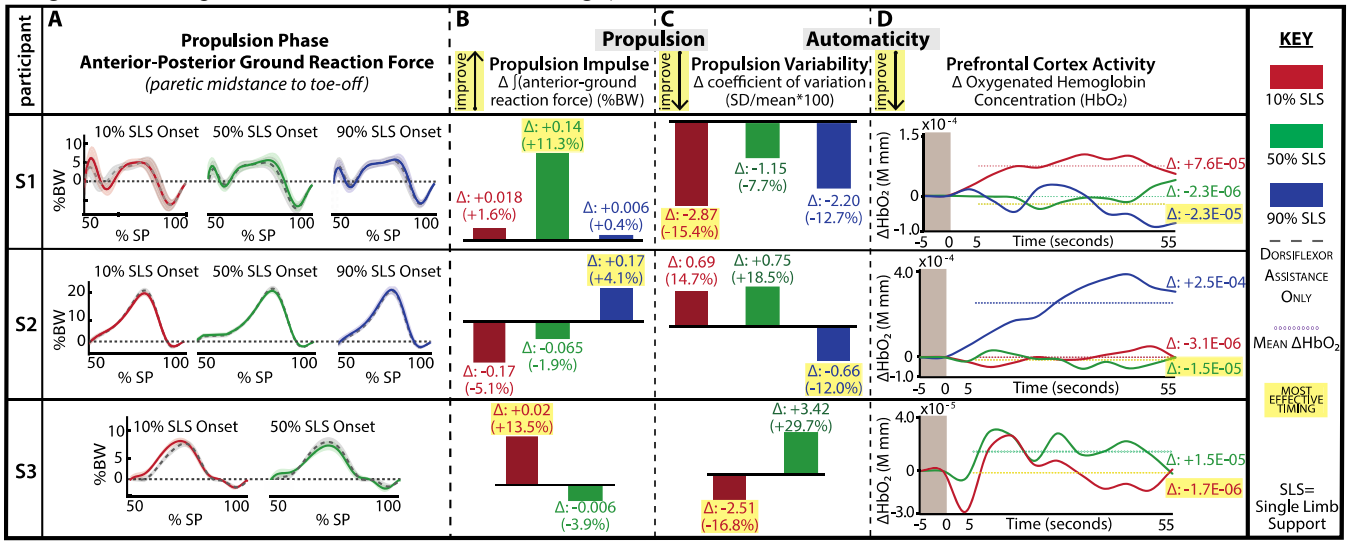

Figure 2. Results: **A**. Anterior-posterior ground reaction forces segmented between propulsion onset to toe-off (i.e., propulsion phase). Mean±SD shown for each tested plantarflexor onset timing (i.e., 10%, 50%, and 90% SLS) superimposed over its respective preceding control condition without plantarflexor assistance. The Y-axis is anterior-posterior ground reaction force normalized by bodyweight (%BW) and the X-axis is time normalized by stance phase time (%SP). **B**. Changes in paretic propulsion impulse, with higher values indicative of improved paretic propulsion through increased anteriorly-directed ground reaction force impulse magnitude. **C**. Changes in paretic propulsion variability, measured as the coefficient of variation (SD/mean*100), with lower values indicative of improved walking automaticity. **D**. Changes in prefrontal cortex activity, measured as Δ oxygenated hemoglobin (HbO_2), with lower values indicative of improved walking automaticity. The most effective plantarflexor onset timing for each outcome is highlighted yellow in **B**, **C**, and **D**.

timing. These findings support the use of a propulsion-augmenting soft robotic exosuit to target deficits in walking automaticity, while emphasizing the importance of individualized tuning of assistance parameters.

From a biomechanical perspective, the intended goal of the plantarflexor assistance provided by the soft robotic exosuit is to increase the magnitude of the propulsion impulse. Our results show that the most effective plantarflexor onset timings to increase the propulsion impulse did not consistently parallel the most effective timings for reducing propulsion variability. In certain contexts, the impact of augmentative systems on biomechanical metrics of automaticity may be important to consider. For example, in the earlier phases of stroke recovery, it may be desirable to facilitate improved step consistency during high intensity, high repetition walking practice. This may require assistance parameters that balance gains in propulsion magnitude and changes in propulsion variability.

From a neurophysiological perspective, reduced prefrontal cortex activity reflects improved walking automaticity. We found that different plantarflexor assistance onset timings differentially affected prefrontal cortex activity across and within subjects. Interestingly, we did not observe large reductions in prefrontal cortex activity; however, some plantarflexor assistance onset timings resulted in substantial penalties (i.e., increases) in prefrontal cortex activity. These findings suggest that using fNIRS-based measurements of automaticity during the exosuit assistance tuning process may aid in avoiding potentially undesirable effects on cognitive load during exosuit-assisted walking.

Soft robotic exosuits elicit changes in both biomechanical and neurophysiological measures of automaticity. These measures appear to provide unique information that cannot be derived from either construct alone. Our findings indicate that it may be critical to consider walking automaticity alongside other locomotor goals when tuning exosuit assistance for each user. Different underlying baseline deficits and use scenarios may guide exosuit prescription, both within and across users, toward prioritizing one locomotor goal over the other. For instance, tuning exosuit assistance profiles to target improved walking automaticity may be critical for use in circumstances where the cognitive demands on walking are higher (e.g., walking while simultaneously thinking). The interactions among these variables present challenges for optimization of assistance profiles, warranting further study and the development of tuning approaches that consider multiple variables.

These preliminary findings demonstrate the importance of considering a multimodal approach to understanding gait automaticity during exosuit-assisted walking and for optimizing the prescription of exosuit assistance profiles. However, there are several important limitations. With three subjects, this study demonstrates that biomechanical and neurophysiological measures of automaticity are sensitive to different plantarflexor assistance onset timings; however, a larger sample is needed to understand how these constructs are related and to inform ways that they can be integrated into a composite measure of automaticity. Additionally, this study did not include kinematic data, which may provide valuable insight into biomechanical variability along the kinematic chain. In this study, all measurements were made during treadmill walking; assessments done overground would increase ecological validity. Further studies are also needed to understand the effects on automaticity of tuning other assistance profile parameters, such as the magnitude of plantarflexor and dorsiflexor assistance. Finally, measuring changes in neurophysiological and biomechanical automaticity alongside standard clinical tests of cognitive load (e.g., as measured using dual task paradigms) would provide new functional insights into the effects of soft robotic exosuits.

V. Significance

Propulsion assistance provided by a soft robotic exosuit can improve post-stroke walking automaticity but requires plantarflexor assistance onset times to be tailored to both users and outcomes to maximize benefits and reduce penalties. Crucially, walking automaticity characterized using measures of biomechanical variability does not respond to soft robotic exosuit intervention in the same way as neurophysiological automaticity. Though biomechanical and neurophysiological measures of automaticity may be conceptually related, they appear to measure different underlying constructs. Both should be considered when the goal is to improve automaticity.

Acknowledgment

We thank our participants for their time and effort.

References

[1] Clark DJ. Automaticity of walking: functional significance, mechanisms, measurement and rehabilitation strategies. *Front Hum Neurosci*. 2015;9:246. doi:10.3389/fnhum.2015.00246

[2] Chen G, Patten C, Kothari DH, Zajac FE. Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds. *Gait Posture*. 2005;22(1):51-56. doi:10.1016/j.gaitpost.2004.06.009

[3] Balasubramanian CK, Bowden MG, Neptune RR, Kautz SA. Relationship Between Step Length Asymmetry and Walking Performance in Subjects With Chronic Hemiparesis. *Arch Phys Med Rehabil*. 2007;88(1):43-49. doi:10.1016/j.apmr.2006.10.004

[4] Balasubramanian CK, Neptune RR, Kautz SA. Variability in spatiotemporal step characteristics and its relationship to walking performance post-stroke. *Gait Posture*. 2009 Apr;29(3):408-14. doi: 10.1016/j.gaitpost.2008.10.061.

[5] Hausdorff JM. Gait variability: methods, modeling and meaning. *J Neuroeng Rehabil*. 2005;2:19. Published 2005 Jul 20. doi:10.1186/1743-0003-2-19

[6] Awad LN, Bae J, O'Donnell K, et al. A soft robotic exosuit improves walking in patients after stroke. *Sci Transl Med*. 2017;9(400):eaai9084. doi:10.1126/scitranslmed.aai9084

[7] Awad, LN, Esquenazi, A, Francisco, GE et al. The ReWalk ReStore™ soft robotic exosuit: a multi-site clinical trial of the safety, reliability, and feasibility of exosuit-augmented post-stroke gait rehabilitation. *J NeuroEngineering Rehabil.* 2020 17;80. https://doi.org/10.1186/s12984-020-00702-5

[8] Hawkins KA, Fox EJ, Daly JJ, et al. Prefrontal over-activation during walking in people with mobility deficits: Interpretation and functional implications. *Hum Mov Sci*. 2018;59:46-55. doi:10.1016/j.humov.2018.03.01

[9] Huppert TJ, Diamond SG, Franceschini MA, Boas DA. HomER: a review of time-series analysis methods for near-infrared spectroscopy of the brain. *Appl Opt*. 2009 Apr 1;48(10):D280-98. doi: 10.1364/ao.48.00d280.

[10] Awad LN, Kudzia P, Revi DA, Ellis TD, Walsh CJ. Walking Faster and Farther With a Soft Robotic Exosuit: Implications for Post-Stroke Gait Assistance and Rehabilitation. 2020 *IEEE Open Journal of Engineering in Medicine and Biology*, 1;108-115 doi: 10.1109/OJEMB.2020.2984429.