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

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***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 multi-objective 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 that constrain users to pre-defined kinematic trajectories, a soft human-robot interface allows unrestricted walking modification. Moreover, a soft interface allows rapid tuning of assistance parameters 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 exosuit-assisted walking improves propulsion symmetry due to increased paretic propulsion, with the amount of paretic limb propulsion output influenced by the prescribed onset timing of plantarflexor assistance. Importantly, individualized tuning of plantarflexor onset timing not only maximized propulsion benefits, but was necessary to avoid timings that reduced paretic propulsion and increased asymmetry[6]. The primary aim of this study was 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 individuals (S1, S2, S3) with chronic stroke (>6 months) were recruited from a research registry to complete

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this preliminary study (age: 46.9±10.4 years; chronicity: 8.2±5.1 years; comfortable walking speed: 1.11±0.39 m/s).

### B. Experiment Overview

Participants completed three 10-min bouts of exosuit-assisted walking on an instrumented treadmill (Bertec Corp., Columbus, OH), each 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**). For all bouts, the magnitude of plantarflexor force was set to 25% bodyweight[6,7]. Although our objective was to evaluate the effects of different paretic plantarflexor assistance onset timings, to ensure safe ground clearance, paretic dorsiflexor assistance was provided during the paretic swing phase in all bouts. The magnitude of dorsiflexor assistance was individualized to each user based on visual gait analysis by a physical therapist[6,7] and held constant across all bouts. Prior to data collection, participants were provided a 1-min acclimation bout for each tested condition.

### C. Soft Robotic Exosuit

The soft wearable robotic exosuit (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 plantarflexor assistance onset timing. Timing of force application 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. 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 impulse 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. Data from the first 30 seconds after each transition were discarded to focus the analysis on steady state walking.

*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 increase the magnitude of paretic propulsion impulse resulted

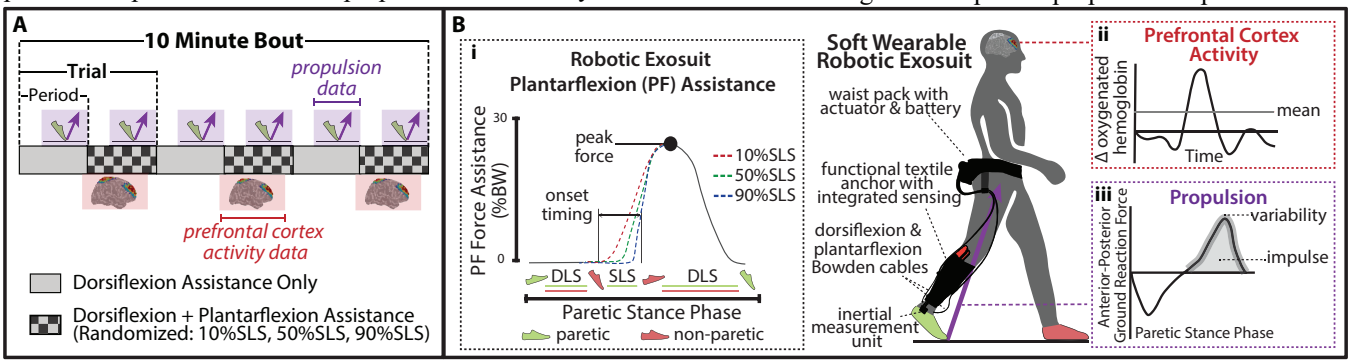


**Figure 1. Methods: A**. Participants completed three 10-minute bouts (one shown); each bout consisted of three repeated trials, with each trial consisting of two periods: the first period tested dorsiflexor assistance only and the next period tested both dorsiflexor and plantarflexor assistance. Plantarflexor assistance onset timing was randomized across bouts. Paretic propulsion and prefrontal cortex activity data were collected in each period as shown. **B**. Soft wearable 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.

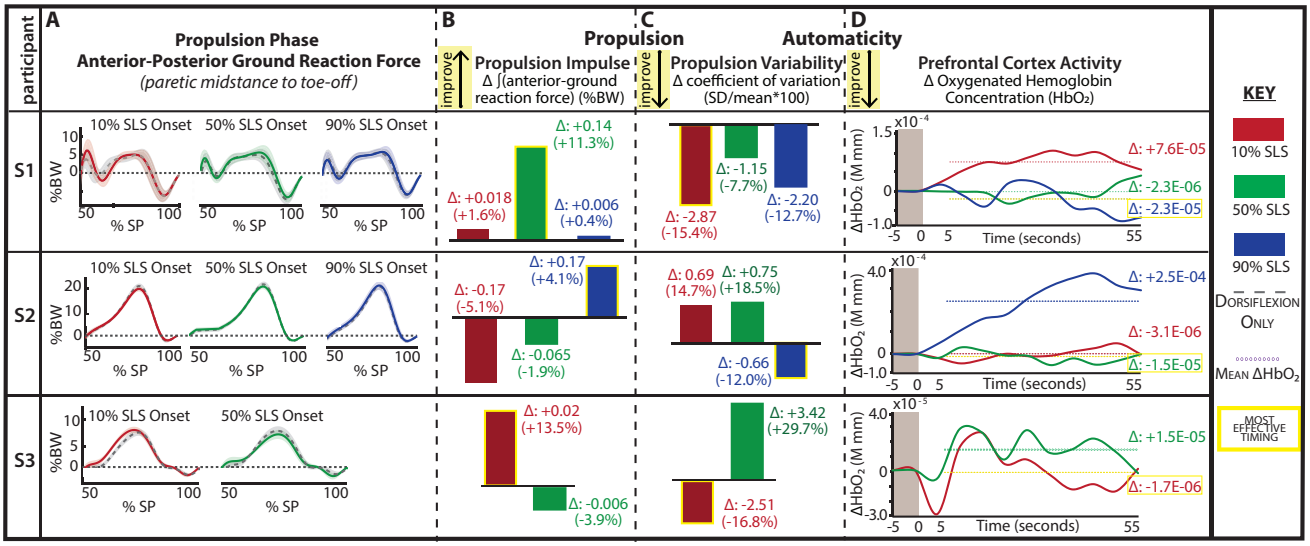


**Figure 2. Results**: **A**. Anterior-posterior ground reactions forces segmented between propulsion onset to toe-off (i.e., propulsion phase). Mean±SD shown for each tested plantarflexor onset timing (i.e., 10%, 50%, and 90% SLS) superimposed over its respective preceding control condition without 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**.

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

Extending our previous studies of the effects of combined paretic dorsiflexor and plantarflexor exosuit assistance versus no assistance[6], 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 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 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. Future studies are needed to understand the effects that tuning other assistance parameters may have on prefrontal cortex activity during walking.

Exosuit-assisted walking elicits 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 is critical to not only individualize tuning of exosuit parameters for each user, but to consider locomotor goals, such as improved paretic propulsion, and the effects on biomechanical and neurophysiological automaticity. Underlying baseline deficits and environmental factors may guide exosuit prescription both within and across users toward prioritizing one of these goals over the other. For instance, targeting metrics of neurophysiological automaticity may be critical for tuning exosuit assistance profiles for use in circumstances that place high cognitive demands on walking, such as walking and talking or thinking. The interactions among these variables present challenges for optimization of exosuit assistance profiles, warranting further investigation and the development of multi-objective tuning approaches.

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 would provide an improved understanding of how these constructs of automaticity are related and allow for statistical analysis. Additionally, this study did not include kinematic data, which may provide valuable insight into biomechanical variability along the kinematic chain. Future studies should also characterize clinical manifestations of increased cognitive demand through assessment of dual task cost in addition to neurophysiological metrics of automaticity.

## 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.

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