Immediate Adaptations to Post-Stroke Walking Performance Using a Wearable Robotic Exoskeleton

Running head: Acute adaptations with hip exoskeleton

Authors: Arun Jayaraman, PT, PhD[1,2†]; Megan K. O'Brien, PhD[1,2]; Sangeetha Madhavan PT, PhD[3]; Kiyoshi Oikawa, MS[4]; Yosuke Endo, MS[4]; Shailesh Kantak, PT, PhD[2,5]; James Stinear, DC, PhD[2,4,6]; T. George Hornby, PhD[7]; William Zev Rymer, MD, PhD[2,8]

† *Corresponding Author*

[1] Max Nader Lab for Rehabilitation Technologies and Outcomes Research, Shirley Ryan AbilityLab, Chicago, IL 60611, USA

[2] Department of Physical Medicine and Rehabilitation, Northwestern University, Chicago, IL 60611, USA

[3] Department of Physical Therapy, University of Illinois at Chicago, Chicago, IL 60612, USA

[4] Fundamental Technology Research Center Honda R&D Co., Ltd., Wako, Japan

[5] Moss Rehabilitation Research Institute, Elkins Park, PA 19027, USA

[6] Department of Exercise Sciences University of Auckland, Auckland, 1072, New Zealand

[7] Department of Physical Medicine and Rehabilitation, Indiana University, Indianapolis, IN 46202, USA

[8] Shirley Ryan AbilityLab, Chicago, IL 60611, USA

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Contact:
Arun Jayaraman
355 E. Erie St., Chicago IL 60611
E-mail: a-jayaraman@northwestern.edu
Tel: 312-238-6875
Fax: 312-238-2000

Acute adaptations to walking using a wearable hip exoskeleton

Immediate Adaptations to Post-Stroke Walking Performance Using a Hip Wearable Robotic Exoskeleton

Abstract

Objective: To examine the immediate effects of a hip-assistive wearable robotic exoskeleton on clinical walking performance, walking energetics, gait kinematics, and corticomotor excitability in individuals with stroke.

Design: Randomized cross-over trial.

Setting: Research laboratory of a rehabilitation hospital.

Participants: Twelve individuals (4F/8M, mean age 57.8±7.2) with chronic hemiparetic stroke.

Interventions: Honda's Stride Management Assist (SMA) exoskeleton, which provides torque-based flexion and extension assistance at the hip joints during walking.

Main Outcome Measures: The primary outcome measure was change in self-selected walking speed with the device off vs. with the device on. Secondary outcome measures included changes in clinical endurance, energy expenditure, kinematics, and corticomotor excitability of lower limb muscles.

Results: In a single session using the device, participants exhibited adaptations over most outcome measures. Self-selected walking speed and peak treadmill speed increased, while oxygen consumption rate decreased during overground and treadmill endurance tests. More symmetric walking patterns were observed during treadmill walking. Changes in corticomotor excitability were highly variable among participants, with a non-significant increase in excitability for the paretic rectus femoris.

Conclusions: The SMA hip exoskeleton causes immediate positive adaptations in walking performance in individuals with stroke when the device is in use.

Key words: intervention; outcomes research; wearable robotics; transcranial magnetic stimulation

Abbreviations

6MWT	Six-Minute Walk Test
ACC	Angular coefficient of correspondence
BWSTT	Body-weight supported treadmill training
EMG	Electromyography
FV	Fast velocity
FWHM	Full Width at Half-Maximum
MEP	Motor-evoked potential
MCID	Minimal clinically important difference
SMA	Stride Management Assist
SSV	Self-selected velocity
RF	Rectus femoris
TA	Tibialis anterior
TM	Treadmill
TMS	Transcranial Magnetic Stimulation
VO2	Oxygen consumption rat

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Introduction

Deficits in sensorimotor control and subsequent disability in ambulation are common manifestations of stroke. Individuals with stroke experience reduced range of motion, insufficient forward and backward propulsion, insufficient weight shift between the non-paretic and paretic legs, muscle atrophy, weakness, and spasticity, resulting in compensatory mechanisms and asymmetrical walking patterns [1-3]. Abnormal hip and pelvis movements compensate for ineffective knee progression and foot clearance. These altered compensatory techniques result in poor walking mechanics, high-energy expenditure, and reduced gait speed [4-6], which contribute to limited community mobility and social interaction [7-8]. As such, improving walking function is often cited as a primary rehabilitation goal for this population [9-14].

Current therapeutic practices emphasize increasing step count to improve post-stroke ambulation. Body-weight supported treadmill training (BWSTT) and robot-assisted gait have shown positive effects on walking ability and function [15-19]. However, in a rehabilitation setting these methods are typically limited to providing stepping practice on a treadmill or constrained environment, and do not provide the challenge and specificity of walking practice over-ground. Unconstrained robotic exoskeletons are promising tools to facilitate gait rehabilitation, as well as supporting community mobility and activities of daily living beyond the clinical environment. At present, a substantial amount of wearable robotics research targets powered lower limb exoskeletons for severe impairments or joint-specific devices, such as the foot and ankle actuation systems [19-22]. Soft robotics has also become an emerging area of research [23], where the devices have little to no rigid material. Preliminary results indicate that one such device has the potential to reduce metabolic cost during walking [24]. However, there are very few studies that have looked at the impact of a light-weight hip wearable robotic exoskeleton on improving walking performance in the stroke population suffering from mild-moderate gait deficits.

The Stride Management Assist (SMA) robotic device was developed by Honda R&D Corporation to enhance walking performance and increase the community mobility and social interaction in elderly adults and patients with gait disorders [25-27]. The SMA provides torque-driven assistance to voluntary movement at the hip joints, augmenting hip flexion and extension independently for each side. In the elderly population, three-month SMA use significantly improved walking speed and reduced glucose metabolism in lower limb muscles [27]. Similarly, previous studies in young adults showed that the SMA increased the walking ratio (step length/cadence) [25] and reduced the metabolic cost of walking over a single session [28]. In individuals with stroke, 6-8 weeks of gait training with the SMA improved clinical outcomes, stepping activity, and corticomotor excitability of the rectus femoris [29], as well as gait kinematics [30], similar to or better than intensity-matched functional gait training without the exoskeleton. At present, the time-course of these improvements is unclear, as are the relative contributions of the device and dosage. It remains to be seen how the SMA affects clinical outcomes in a single session for a neurologically impaired population. The impact of a single training session is of interest to therapists and clinicians so they can quickly determine whether an intervention is appropriate for an individual patient. This would help them design training dosages (or decide to pursue other interventions) to maximize and maintain clinical outcomes for each patient.

The purpose of this preliminary study was to examine the immediate effects of walking with the SMA on functional walking ability in individuals post-stroke. We tested the hypothesis that a single session of walking with the SMA would elicit immediate adaptations in gait, including walking speed, energetics, kinematics, and corticomotor excitability of lower limb muscles. We measured gait outcomes while the SMA was both active and inactive, to account for potential secondary effects of wearing the exoskeleton on gait (e.g. added mass, physical structure, and placebo effects).

Methods

Participants

Twelve individuals with chronic unilateral stroke were recruited (4F/8M, mean age 57.8±7.2). Demographic information for all participants is listed in Table 1. All participants were able to walk independently on level ground, and were allowed to use assistive devices or bracing as needed during training and testing. The study was approved by the IRB at the Northwestern University, and all participants provided written consent.

Inclusion criteria for the study were: 1) history of one unilateral, supratentorial, ischemic or hemorrhage stroke, with lesion location confirmed by radiographic findings, 2) gait speed less than 0.8 m/s (limited community ambulators), as measured through a 10-Meter Walk Test, and 3) medically stable with medical clearance to participate (absence of concurrent illness, including unhealed decubiti, infection, cardiopulmonary disease, osteoporosis, active heterotrophic ossification, peripheral nerve damage in the lower limbs, and a history of traumatic head injury). Exclusion criteria for the study were: 1) body weight of more than 250 lbs, which is the limit of most counter-weight safety systems, and 2) pregnancy, due to potential forces at trunk from BWS or pelvic assistance. Exclusion criteria for measuring corticomotor excitability using Transcranial Magnetic Stimulation (TMS) were: pacemaker, metal implants in the head region, history of epilepsy or seizures, skull fractures or skull deficits, concussion within the last 6 months, unexplained recurring headaches, medications that lower seizure threshold, and pregnancy.

SMA Device

The Stride Management Assist (SMA) is a robotic device developed by Honda R&D Corporation (Japan), which assists hip flexion and extension for each leg independently. The SMA is worn around the waist like a belt, with 2 brushless DC motors at the hip joints that generate assistive torque, transmitted to the legs via frames at the mid-thigh. The device is operated using custom software on a tablet, which allows the user or a physical therapist to change assist settings while the user is wearing the SMA. The device weighs 2.8 kg, with a rechargeable lithium ion battery. The operation time is approximately 2 hours on a single charge for continuous walking at 4.5 km/hour.

The SMA control architecture uses a mutual rhythm scheme to influence the user's walking patterns. Angle sensors embedded in the SMA actuators detect the user's hip joint angles throughout the gait cycle. These angles are input to the SMA controller, which calculates hip joint angle symmetry. The device then generates assistive torques at specific instances during the gait cycle to regulate these walking patterns. The user initiates walking and controls their walking speed. After initial contact, the extensor torque initiates and reaches its peak just before mid-stance. The SMA then switches to flexion assist during terminal stance. The flexor torque reaches its peak around initial swing. Finally, the SMA switches to extension assist during terminal swing, and the cycle repeats. Peak torque values for flexion and extension ultimately depend on user input. While the SMA is capable of outputting a maximum of 6 Nm of assist torque, peak torque values are contingent upon user hip joint dynamics determined from the angle sensors. The SMA automatically manipulates the walking motion to increase walk ratio (step length/cadence) providing torque assistance during hip flexion and extension movements when walking is initiated. For example, if the SMA detects hip joint angle asymmetry, then the SMA assist pattern follows a more flexion dominant curve for the leg with shorter stride length, in an attempt to better support the user. Depending on user hip joint angles, the peak flexor torque may be less than 6 Nm. The SMA is designed to provide assistance only in the sagittal plane; it does not restrict movement in other directions.

Randomization and training protocol

A randomized cross-over design (Fig. 1) was implemented in this study. Participants were stratified to either a device-on (ON) or device-off (OFF) condition. Outcome measures were collected under this condition in a single session. After one week, the participant crossed-over to the other condition and the same measures were collected in a single session. Because all participants completed both conditions, they acted as their own controls. All participants were acclimated to the device with a single 30-45-minute training session with a licensed physical therapist. In this session, therapists introduced the device and participants practiced walking with the device in a 12-m long hallway, with rests as needed. Participants first walked with the device donned but turned off, then the therapist turned the device on and provided contact guarding until the participant felt comfortable walking independently under supervision. Once the therapist was satisfied that the participant could walk safely, independently, and comfortably with the device under supervision, the participant was randomly assigned to the ON or OFF condition without being told to which group they were assigned. At least one week was required between conditions to allow for wash-out.

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Testing and evaluation protocol

The primary outcome measure was change in self-selected walking speed between the ON and OFF conditions. The secondary outcome measures were changes in fast walking speed, endurance, energetic efficiency, kinematics, and corticomotor excitability of paretic lower limb muscles between the two conditions. The measures and procedures are described below.

- Self-selected walking velocity (SSV) and fastest walking velocity (FV): Participants walked in a straight line on an instrumented walkway (GaitMat II®, Equitest Inc, Chalfont) using their self-selected pace and fastest safe pace. Three trials were averaged at each speed.

- Six-minute walk test (6MWT): Participants were instructed to cover as much distance as possible during six minutes. They walked up and down a straight hallway, and distance was measured.

- Graded treadmill test: Participants walked on an instrumented treadmill with harness but no body weight support. Testing started at 0.5 km/h and was increased in 0.5 km/h increments every 3 minutes until peak treadmill speed was achieved (identified as ability to sustain speed for ≥1min without stopping the treadmill).

- Energetic efficiency: Oxygen consumption rate (VO2) were measured during the six-minute walk test and graded treadmill test from a portable metabolic system (K4b2, CosMed Srl., Rome, Italy). Baseline measures were obtained during five minutes of sitting immediately prior to walking.

- Kinematic measures during SSV treadmill walking: Lower extremity kinematic data were collected using a motion analysis system (Motion Analysis Corp, Santa Rosa, CA). The system includes six strategically positioned charge-coupled device video cameras (VC491; Oxford Metrics), a minicomputer (PDP 11/73; Digital Equipment, Maynard, MA), and software (Visual 3D, C-motion; Germantown, MD) for the collection and analysis of the data. Twenty-one spherical reflective markers, one inch (25.4 mm) in diameter, were placed over predetermined anatomical landmarks on the trunk and the upper and lower extremities using the modified Cleveland Clinic Marker Set (Motion Analysis Corporation, Santa Rosa, CA). The SMA and other reflective surfaces were covered with non-reflective tape. Participants walked on a treadmill at the speed determined from the over-ground SSV measure. A harness attached to the suspension system was used for fall prevention, with no body weight support. Position coordinates for the markers on both sides of the body were recorded simultaneously at 100 Hz with use of the phase-locked cameras. This allowed for the three-dimensional reconstruction of the motion of all of the major joints of the upper and lower extremities.

- Angular coefficient of correspondence (ACC) [31-32]: hip/knee kinematics were assessed bilaterally to determine the consistency of sagittal plane hip/knee trajectories, calculated by vector coding. The difference between each successive motion frame for hip angle values and knee angle values was transformed into a vector, with both direction and magnitude, using the methods described in [31]. This vector was computed in 1% increments of the normalized gait cycle. The ACC is an average of all vector lengths, representing the degree of consistency between hip and knee angles across multiple gait cycles. An ACC of 1.0 signifies perfect consistency, wherein the relative motion between the hip and knee are in complete agreement over all gait cycles. An ACC of 0.0 signifies no consistency between hip and knee angles. Positive changes in ACC indicate improved coordination of a limb.

- Full Width at Half-Maximum (FWHM) [33]: the periodogram of stepping frequency was created from the data obtained using an electronic goniometer at the hip joint. Maximum power was determined at the appropriate frequency (consistent with cadence estimates). The width of the peak at half-maximum power was then calculated in Hz. Low values of FWHM indicate rhythmic and periodic stepping, whereas high values suggest erratic stepping, such as stumbling or foot dragging [34]. Negative changes in FWHM indicate improved periodicity in stepping patterns.

- Corticomotor excitability (CME): motor-evoked potentials (MEPs) estimated excitability of the paretic rectus femoris (RF – hip flexor and knee extensor) and tibialis anterior (TA – ankle dorsiflexor) during SSV treadmill walking. MEPs were induced using transcranial magnetic stimulation (TMS), A double cone coil (Magstim 200, Wales, UK) delivered TMS at a minimum frequency of 0.25 Hz, localized on the muscle hotspot in accordance with [35]. A hotspot is the location on motor cortex producing the maximum MEP response for the contralateral muscle at the lowest stimulator intensity. For RF, MEPs were evoked at 120% active motor threshold, determined during points in the gait cycle that corresponded to the muscle's peak activation. For TA, motor excitability was probed during late swing to maintain consistency with previous studies [36-37]. During walking, electromyography (EMG) containing 10 MEPs per muscle was recorded during the ON and OFF conditions. The averaged MEP area as a percentage of background activity was calculated for each response. For each participant, we then calculated a percentage normalized to the change in the MEP amplitude for each muscle with the device ON compared to when the device was OFF.

TMS Protocol

A previously established TMS protocol was employed to obtain measures of CME during walking [36-37]. A pulley system supported the TMS coil cable over the participant's head. Coil position was primarily maintained by Velcro® tapes secured between the inside of the coil and the top of a linen cap. Slight adjustments to the coil position were made until MEPs ≥ 0.4 mV were elicited from TA with minimal TMS intensity. A chin strap was then attached to the coil, and foam pads were inserted between the head and the lateral aspects of the coil to increase stability of the placement. This allowed subjects to walk naturally and move their head freely between trials without disturbing the coil location. Coil position was checked frequently during data collection, and no changes were detected for any participant.

Following data collection, pre-trigger root mean square EMG amplitude (mV r.m.s.) was calculated for the 40 ms of data just prior to the stimulus, and MEP amplitude (mV peak-to-peak) was calculated using custom code in Matlab (MathWorks, Natick, MA).

To match for similar levels of background activity across time periods, responses were discarded if they were associated with high or low amplitude pre-trigger EMG to bring the range and mean pre-trigger EMG amplitudes for each subject and muscle to within 2%. After this processing, typically 10 responses remained for each condition.

Statistical Analysis

Paired sample t-tests were performed for all raw measures to compare the ON and OFF conditions, since all participants were their own controls and the test of normalcy showed a normal distribution of the data. For CME, one-sample t-tests were performed to compare the percentage change in CME to 0. The significance level was set at $p<0.05$. The 95% confidence intervals are reported for the difference between ON and OFF conditions. All statistics were performed in SPSS Version 20 (IBM Co., NY).

Sample Size Estimation

Sample size was chosen using a superiority test with cross-over design [38]. The superiority margin was taken as the suggested Minimal Clinically Important Difference (MCID) for the primary outcome, walking speed. MCID for self-selected walking speed for a stroke population was taken as 0.06 m/s [39]. To achieve 80% power with a significance level of 0.05 and an estimated population variance of 0.01 m/s, the sample size is 9 participants.

Results

Changes in the outcome measures between the ON and OFF conditions are given in Table 2 for each participant. The primary outcome measure, self-selected walking speed, is shown in Figure 2 for the baseline (not wearing the device), and with the device OFF and ON. Paired t-tests reveal no significant difference in SSV between baseline and the OFF condition (p=0.13). Self-selected walking speed increased by 8.6% (SEM 2.8) with the SMA in the ON condition (Fig. 3A; p=0.012; 95% CI = [0.008, 0.097] m/s). There was no difference in fast velocity (p=0.96; 95% CI = [-0.061,0.058] m/s).

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Peak treadmill speed tolerated also increased during the graded treadmill test (Fig. 3B; p<0.001; 95% CI = [0.08, 0.14] m/s). Average distance walking during the 6MWT increased, though this difference was non-significant (p=0.061; 95% CI = [-1.8, 66.5] m). Maximum and average VO2 costs decreased in the graded treadmill test (p=0.024; 95% CI = [-0.14, 0.03] mL/kg/km) and 6MWT (p=0.019; 95% CI = [-67.6, -2.3] mL/kg/km), respectively (Fig. 3C).

Intralimb kinematic variability, measured using average ACC, increased on the paretic and non-paretic sides with the SMA ON (Fig. 3D; p's<0.001; 95% CI = [0.030, 0.096] paretic, [0.093, 0.12] non-paretic). Stepping periodicity, measured using FWHM, also decreased in both the affected and unaffected sides of the stroke participants (Fig. 3E; p's<0.017; 95% CI = [-0.017, -9.0×10^{-4}] paretic, [-0.019, -4.3×10^{-4}] non-paretic).

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Changes in CME are presented from the paretic RF and TA muscles in Fig. 3F. We were able to elicit MEPs in the RF muscle in 11 of the 12 participants. Average excitability of the paretic RF increased by 20.8% (SEM 11.2), though this was non-significant (p=0.095; 95% CI = [-3.9, 41.9] %). Of the 11 participants, nine showed an increase in the MEP amplitude with the device ON compared to when the SMA was OFF. This increase in MEP amplitude ranged from 2% to 90%, indicating a high variability in CME in response to the exoskeleton assistance. We were able to evoke an MEP from the TA in 10 of the 12 participants. Average excitability of the paretic TA decreased by 14.8% (SEM 10.9), though this was non-significant (p=0.18; 95% CI = [-34.5, 7.5] %). Of the 10 participants, seven showed a decrease in the MEP amplitude with the device ON compared to when the SMA was OFF. Two participants showed small increases, and one showed a large increase in MEP amplitude with the device ON.

Discussion

Over a single session of use with the SMA hip device, we found significant improvements in measures of walking performance in chronic stroke patients. Self-selected walking speed and spatiotemporal gait symmetry increased with SMA use. Our results also indicate that assistance from the SMA enabled patients to maintain a higher rate of speed while consuming less oxygen. These findings confirm that a hip-assistive exoskeleton elicits an immediate impact or adaptation on walking and functional capabilities in individuals with chronic stroke and mild-moderate gait impairments.

The cross-over study design, in which measures were taken with the device OFF and ON, was selected to minimize the potential of a placebo effect of wearing a gait-assistive device designed by large commercial manufacturer such as Honda. The SMA in its ON mode increased self-selected walking speed in these participants with mild-moderate gait impairment. Our previous work has shown that long-term SMA training specifically increases stride length while decreasing double support time and swing time [30]. Changes in walking speed were not observed in the fast velocity condition.

During the graded treadmill test, participants were able to reach higher maximum walking speeds on the treadmill with the device in ON mode. Improvements in exercise capacity were substantiated by measures of energy efficiency, where the oxygen consumption rates were reduced in both the graded treadmill and six-minute walk tests. This has been shown previously in younger adults walking with the SMA over a single session [28]. Traditionally, increased metabolic demands during gait training has been noted as a limiting factor in the administration of physical therapy and rehabilitation [40-42]. This makes the SMA a promising exercise/therapeutic tool, since reducing the metabolic demand during strenuous gait training may enable greater walking-related gains post-stroke. Similarly, during the six-minute walk test, most participants were able to walk farther distance with lower metabolic cost. This suggests that the future SMA may be useful as a walking-assistive personal mobility device, as it may encourage participants to walk more at home and in the community without the fear of fatigue and meeting the demands of navigating the community environment.

Evaluations of kinematic behavior indicated improvements in spatiotemporal symmetry. This agrees with our previous findings of increased symmetry after long-term training with the SMA [30]. In the current study, these improvements were observable during single-session use of the SMA, suggesting the effects of the repetitive movement provided by the SMA has short-term kinematic benefits. Increases in ACC during the SMA in ON mode versus OFF mode reveal increased consistency between hip and knee angles on both the paretic and non-paretic sides. Higher ACC is strongly correlated to improved walking function [32, 43]. Walking with the SMA in ON mode also reduced FWHM on both the paretic and non-paretic sides, indicating more rhythmic and consistent stepping with the SMA torque assistance. This might be useful in training efficiency, as well as helping to prevent falls, which may be related to spatiotemporal asymmetry and inconsistent stepping patterns [44].

Amplitude of motor evoked potentials increased more consistently for the rectus femoris muscle on the paretic side, which indicates that the SMA in ON mode increases corticomotor excitability of the damaged side of the brain. The consistent hip flexion motor and sensory assistance from the SMA resulted in potentially activating the damaged side of the cortex to increase its signal transmission. We have seen that long-term training with the SMA increases excitability of the paretic rectus femoris during voluntary contraction [29]. Conversely, neither this single session nor long-term training affects corticomotor excitability of the tibialis anterior. An alternative exoskeleton design with assistance as the ankle joint may be required to elicit a more pronounced response for this muscle group.

Comparison to MCID

The MCID for a stroke population is suggested to be 0.06 m/s for walking speed (small meaningful change) [39] and 34.4 m for 6MWT [45]. Average changes in self-selected walking speed (0.05 m/s) and 6MWT distance (32.3 m) fell short of MCID for a single session of SMA use. At the individual level, three participants exceeded MCID for walking speed, and six participants exceeded MCID for 6MWT. Future work will compare single session adaptations with long-term training to further uncover the impact of SMA dosage on clinically-relevant outcomes and the predictors of response to this training.

Study Limitations

A major limitation of the current study is its small sample size with similar levels of gait impairment. It remains to be seen how the device affects walking function in a more impaired population, or in the subacute phase of stroke. Additionally, baseline measures, in which participants did not wear the exoskeleton, were not taken for all outcomes. We only measured self-selected walking speed at baseline, under the assumption that the SMA in OFF mode was equivalent SMA being off the body due to its light weight (2.8 kg). It is also possible that the training-induced changes in our MEP data were confounded by physiologic factors such as lesion location, muscle activity, alertness, or by technical factors such as intensity of stimulation and location of coil, which would diminish our ability to detect changes in corticomotor excitability.

Conclusions

This study reveals that a single session of SMA use elicits immediate adaptations in clinical walking performance, walking energetics, and gait kinematics. Improvements in walking performance are seen both on the treadmill and over-ground walking function, along with improvements in stepping consistency and periodicity. Future work will further examine the time-course of adaptation and wash-out to the SMA across single and multiple training sessions, as well as the usability of the SMA in the home and community environment as an everyday personal mobility device. The immediate adaptations seen with the SMA allows clinicians to test the device with their patients during a single session and deem whether it is appropriate for them during therapy.

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Figure Legends

Figure 1: Experimental design. Participants were their own controls in this randomized cross-over trial. Outcome measures were taken with the SMA device turned OFF and ON.

Figure 2: Self-selected walking speed. SSV at baseline (without the SMA), with the SMA turned OFF, and with the SMA ON. Error bars represent SEM.

Figure 3: Change in outcome measures between OFF and ON conditions. Percentage change in (A) walking speed in the SSV and FV conditions, (B) peak treadmill (TM) speed and distance walked during 6MWT, (C) maximum and average oxygen consumption rate during the graded TM test and 6MWT, respectively, (D) ACC of the paretic and non-paretic leg, (E) FWHM of the paretic and non-paretic leg, and (F) corticomotor excitability (CME) of the RF and TA. Error bars represent SEM. Asterisks (*) indicate significant difference between the ON and OFF conditions (paired t-tests).

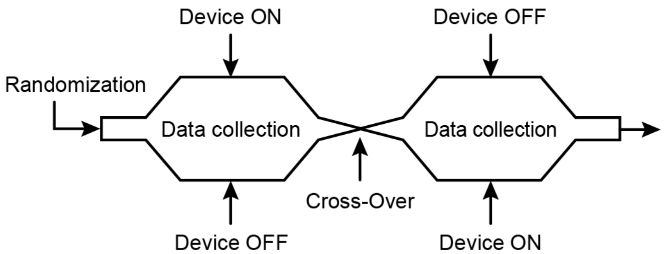
Tables

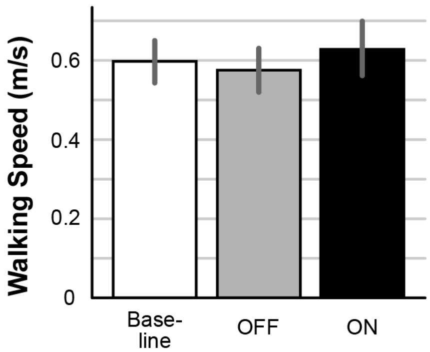
Table 1: Participant demographics at baseline

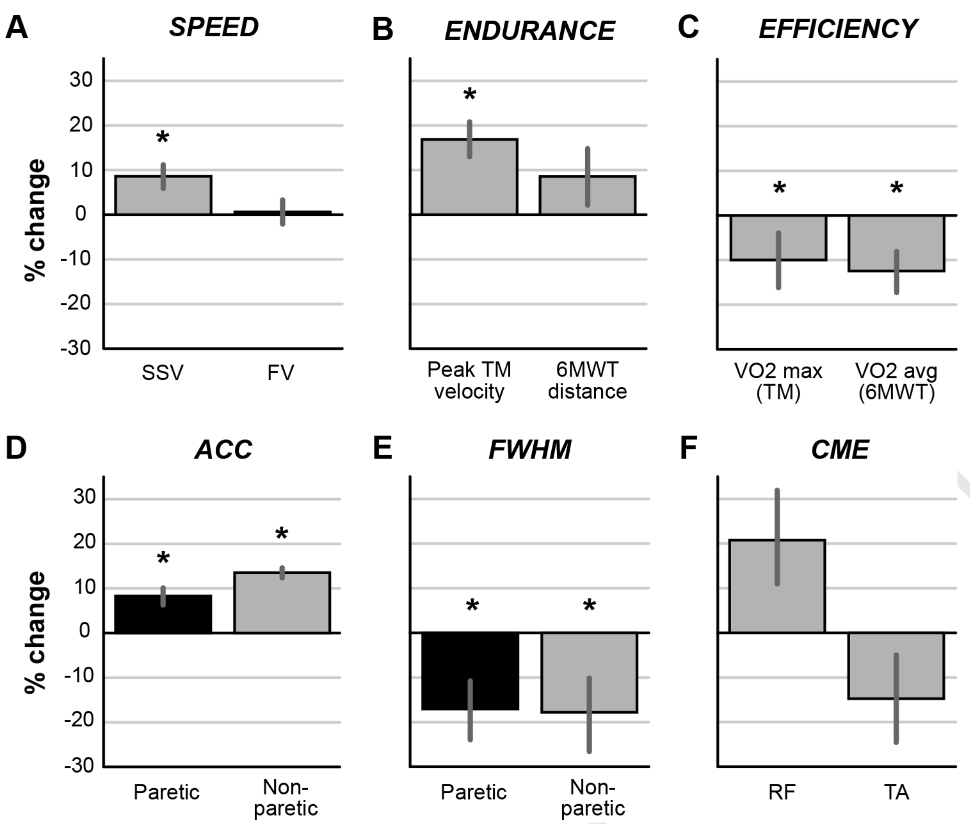
ID	Sex (M/F)	Age (years)	Stroke latency (years)	Stroke type	Side affected (R/L)	Assistive Device	Bracing	Initial gait speed (m/s)
S1	F	63	13	Unknown	R	Straight Cane	AFO	0.36
S2	M	65	14	Hemorrhagic	R	Quad Cane	None	0.70
S3	M	64	20	Hemorrhagic	L	Straight Cane	AFO	0.36
S4	M	48	10	Hemorrhagic	L	Straight Cane	None	0.70
S5	M	70	22	Hemorrhagic	L	None	AFO	0.70
S6	F	54	11	Ischemic	L	Straight Cane	AFO	0.75
S7	F	57	28	Ischemic	R	Straight Cane	AFO	0.79
S8	M	61	21	Hemorrhagic	R	Straight Cane	None	0.32
S9	M	58	8	Hemorrhagic	R	None	None	0.70
S10	M	55	11	Ischemic	R	None	None	0.75
S11	F	54	12	Ischemic	R	None	None	0.37
S12	M	45	5	Unknown	R	None	AFO	0.67

Table 2: Changes in outcomes between SMA conditions (ON-OFF)

ID	SSV (m/s)	FV (m/s)	6MWT		Graded endurance test		ACC		FWHM	
			Distance (m)	*VO2 avg (mL/kg/km)*	*Peak vel (m/s)*	*VO2 max (mL/kg/km)*	*Non-paretic*	*Paretic*	*Non-paretic*	*Paretic*
S1	0.05	-0.08	36.7	-10.46	0.1	0.04	0.148	0.073	-0.043	-0.035
S2	0.26	0	39.9	-11.75	0.1	-0.01	0.113	0.024	-0.013	-0.013
S3	0.03	0.03	-25.3	-122.76	0	-0.07	0.102	0.147	-0.010	-0.005
S4	0.04	-0.03	34.3	-134.97	0.1	-0.20	0.104	0.124	-0.003	0.000
S5	0.10	-0.20	63.0	28.19	0.1	-0.05	0.090	0.130	-0.003	-0.003
S6	0.04	0.02	76.0	-49.55	0.2	-0.11	0.104	0.080	-0.023	-0.025
S7	0.02	0.07	-37.0	-15.29	0.1	0.01	0.150	0.043	-0.005	-0.008
S8	0.01	0.18	-30.8	-51.06	0.2	-0.43	0.094	0.032	0.020	0.015
S9	0.07	0.03	14.0	-38.57	0.1	-0.01	0.078	-0.023	-0.010	-0.010
S10	0.01	-0.10	11.1	-5.59	0.1	-0.02	0.103	0.010	-0.010	-0.008
S11	0.01	0.05	157.3	-39.16	0.1	-0.03	0.097	0.037	-0.013	-0.010
S12	0.01	0.03	49.0	31.92	0.1	0.01	0.097	0.079	-0.005	-0.005
Mean (SEM)	**0.05 (0.02)**	**0.00 (0.03)**	**32.3 (15.5)**	**-34.92 (14.84)**	**0.11 (0.02)**	**-0.08 (0.04)**	**0.104 (0.006)**	**0.064 (0.015)**	**-0.010 (0.004)**	**-0.009 (0.003)**


Device ON
Device OFF
Randomization
Data collection
Data collection
Cross-Over
Device OFF
Device ON


Walking Speed (m/s)
0.6
0.4
0.2
0
Base-
line
OFF
ON


A
SPEED
B
ENDURANCE
C
EFFICIENCY
% change
30
20
10
0
-10
-20
-30
*
SSV
FV
Peak TM velocity
6MWT distance
VO2 max (TM)
VO2 avg (6MWT)
D
ACC
E
FWHM
F
CME
Paretic
Non-paretic
RF
TA