Published in final edited form as:

Restor Neurol Neurosci. 2018 ; 36(2): 215–223. doi:10.3233/RNN-170782.

A Wearable Resistive Robot Facilitates Locomotor Adaptations during Gait

Edward P. WASHABAUGH^{a,b} and Chandramouli KRISHNAN^{a,b,*}

^aNeuRro Lab, Department of Physical Medicine and Rehabilitation, Michigan Medicine, Ann Arbor, MI, 48108 USA

^bDepartment of Biomedical Engineering, University of Michigan, Ann Arbor, MI, 48109 USA

Abstract

Background—Robotic-resisted treadmill walking is a form of task-specific training that has been used to improve gait function in individuals with neurological injury, such as stroke, spinal cord injury, or cerebral palsy. Traditionally, these devices use active elements (e.g., motors or actuators) to provide resistance during walking, making them bulky, expensive, and less suitable for overground or in-home rehabilitation. We recently developed a low-cost, wearable robotic brace that generates resistive torques across the knee joint using a simple magnetic brake. However, the possible effects of training with this device on gait function in a clinical population are currently unknown.

Objective—The purpose of this study was to test the acute effects of resisted walking with this device on kinematics, muscle activation patterns, and gait velocity in chronic stroke survivors.

Methods—Six stroke survivors wore the resistive brace and walked on a treadmill for 20 minutes (4 × 5 minutes) at their self-selected walking speed while simultaneously performing a foot trajectory-tracking task to minimize stiff-knee gait. Electromyography, sagittal plane gait kinematics, and overground gait velocity were collected to evaluate the acute effects of the device on gait function.

Results—Robotic-resisted treadmill training resulted in a significant increase in quadriceps and hamstring EMG activity during walking. Significant aftereffects (i.e., improved joint excursions) were also observed on the hip and knee kinematics, which persisted for several steps after training. More importantly, training resulted in significant improvements in overground gait velocity. These results were consistent in all the subjects tested.

Conclusion—This study provides preliminary evidence indicating that robotic-resisted treadmill walking using our knee brace can result in meaningful biomechanical aftereffects that translate to overground walking.

*Corresponding author: Chandramouli Krishnan, Director, Neuromuscular & Rehabilitation Robotics Laboratory (NeuRro Lab), Department of Physical Medicine and Rehabilitation, University of Michigan, 325 E Eisenhower Parkway (Suite 3013), Ann Arbor, MI - 48108, Phone: (319) 321-0117, Fax: (734-615-1770); mouli@umich.edu.

Keywords

Rehab robotics; EMG; Task-specific; Active engagement; Functional resistance training; Rehabilitation

Introduction

Individuals with stroke often experience significant walking dysfunction that limits their ability to safely and effectively ambulate in the community (Michael et al., 2005). Indeed, current evidence indicates that reduced gait speed is a significant predictor of falls and mobility outcomes after stroke (Michael et al., 2005; Ng et al., 2017). Thus, regaining locomotor function is a major goal of post-stroke rehabilitation (Teasell et al., 2003), and therapists often place a considerable amount of time and effort in restoring gait function after stroke.

Treadmill training and progressive resistance training are the two most commonly used techniques to improve locomotor function after stroke (Leon et al., 2017; Manella and Field-Fote, 2013; Pak and Patten, 2008; Polese et al., 2013; Seo et al., 2017; Visintin et al., 1998). These interventions have demonstrated improvements in gait performance, although outcomes are known to vary between studies, particularly for resistance training (Lamberti et al., 2017; Lund et al., 2017; Mehta et al., 2012; Nadeau et al., 2013; Park et al., 2015; Vahlberg et al., 2017). It is to be noted that resistance training is typically performed in a “nonfunctional” manner (e.g., exercises performed in seated or standing positions); whereas, it is known that training should be functional (i.e., specific to the task being targeted) to address sensorimotor deficits during functional tasks, such as walking because of practice specificity (Barnett et al., 1973; Dobkin, 2004; El Amki et al., 2017; Henry, 1968; Kleim and Jones, 2008; Manini et al., 2007; Proteau et al., 1992; Schmidt and Lee, 1988; Takahashi et al., 2008; Williams et al., 2014). Further, such training of isolated muscle groups (without any functional context) does not facilitate the synchronized activation of multiple muscles (i.e., coordination), which is critical for gait recovery after stroke. Thus, interventions that collectively address strength and coordination deficits during walking could be beneficial for improving gait function after stroke.

Task-specific loading of the limbs—termed as functional resistance training or functional strength training—combines elements of resistance training and task-specific training for gait rehabilitation. Here, resistance is applied to the subject’s limb during walking such that multiple muscles are engaged in a coordinated fashion (Gama et al., 2017; Washabaugh et al., 2016). A number of studies have evaluated the benefits of functional resistance training in healthy as well as neurologically impaired individuals. These studies collectively demonstrate that functional resistance training can (1) improve metabolic rate, (2) increase lower-extremity muscle activation, joint power, and kinematics, and (3) improve skilled overground walking performance (e.g., gait speed, endurance, balance, symmetry, etc.) (Browning et al., 2007; Duclos et al., 2014; Houldin et al., 2011; Klarner et al., 2013; Lam et al., 2015; Lam et al., 2011; Wu et al., 2014a; Wu et al., 2014b; Wu et al., 2012; Wu et al., 2011; Yen et al., 2012). However, functional resistance training is often performed using

devices with active elements, such as motors or actuators, to control the resistive forces/torques, which makes them bulky, expensive, and less suitable for overground or in-home rehabilitation. Further, these training methods typically do not incorporate any kinematic feedback during resisted walking, which is critical to incentivize participants to increase effort and maintain optimal spatiotemporal coordination.

To address these issues, we recently developed a low-cost, wearable robotic knee brace that is capable of producing scalable resistive torques using a simple magnetic brake (Washabaugh et al., 2016), and tested the biomechanical effects of this device on healthy, unimpaired individuals during treadmill walking. The training also incorporated a foot trajectory-tracking paradigm to ensure that subjects maintained appropriate hip/knee kinematics during resisted walking. The results of this study demonstrated that resisted walking significantly increased muscle activation of the lower-extremity muscles and induced kinematic aftereffects once the resistance was removed. However, the possible effects of training with this device on gait function in a clinical population—which is critical to understand the clinical potential of this device—are currently unknown. Therefore, this study tested the acute effects of resisted treadmill walking on quadriceps and hamstring muscle activation patterns, sagittal hip/knee kinematics, and overground gait velocity in chronic stroke survivors. We hypothesized that resisted treadmill walking will significantly increase muscle activation, hip and knee excursion, and gait velocity: these hypotheses were based on our prior experience with healthy adults (Washabaugh et al., 2016) and on existing literature in neurologically impaired individuals (Lam et al., 2011; Wu et al., 2012; Yen et al., 2012).

Materials and Methods

Participants

Six (3 males and 3 females) chronic stroke survivors (Age: 58.0 ± 8.5 years, Height: 1.70 ± 0.14 m, Weight: 76.0 ± 23.6 Kg, Time since stroke onset: 3.0 ± 2.7 years, Lower-extremity Fugl-Meyer score: 27.8 ± 6.2 [maximum possible = 34]) participated in this research study. Stroke subjects were included in this study if they 1) were between 18 and 75 years of age, 2) had a unilateral stroke at least 6 months prior to participation, 3) had a cortical or sub-cortical lesion that was documented by radiological (CT or MRI) or clinical findings, 4) were community ambulators and indicated that they can walk at least 20 minutes on a treadmill, and 5) had some ability to bend their hip and knee. Exclusion criteria included: 1) a history of a recent lower-extremity injury, fracture, or surgery, 2) uncontrolled diabetes or hypertension, 3) Mini-Mental State Exam score < 22 , and 4) a history of unstable or untreated cardiovascular diseases. All subjects provided written informed consent to participate in the study using a form that was approved by the University of Michigan Institutional Review Board.

Wearable Robotic Brace

Functional resistance training was performed using a resistive brace that was engineered with an eddy current brake. An in depth description of this device is provided elsewhere (Washabaugh et al., 2016). Briefly, eddy current brakes are non-contact brakes that utilize

the motion of a conductive material through a magnetic field (an act that creates eddy currents within the conductive material) to generate dissipative resistance to that motion. The magnitude of the resistive torques generated by an eddy current disk brake (as used in this device) is governed by: $\tau = \sigma \times A \times d \times B^2 \times R^2 \times \omega$ (Gosline and Hayward, 2008). In this equation, the resistive torque τ depends on the conductivity of the disc material σ , area of the disc exposed to the magnetic field A , the thickness of the disc d , the magnitude of the magnetic field strength B , the effective radius of the disc R , and the angular velocity of the disc rotation ω (Fig. 1a). Hence, magnitude of the resistance can be augmented by altering the area of the magnetic field exposed to the disk (i.e. greater magnetic exposure will result in greater resistive torques).

The eddy current brake of our device consists of two permanent magnets (DX04B-N52, KJ Magnetics, Pipersville, Pa) mounted on a ferromagnetic backiron, a planetary gearbox (P60, Banebots, Loveland, CO), and an aluminum disc (0.5 cm thickness, 10.16 cm diameter). The magnets and backiron are fixed to a linear slider, which allows us to control the magnitude of the resistance (Fig. 1b). To properly convey the resistive torques to the user, the brake interfaces with a commercially available knee brace (Fig. 1c) (T Scope Premier Post-Op Knee Brace, Breg, Grand Prairie, TX). When this brace is worn, flexion or extension of the knee spins the aluminum disc and generates resistive torque to oppose this motion (via eddy currents) based on how the magnets are exposed to the disk.

Experimental Protocol

The schematic of the experimental protocol is provided in Fig. 2. Prior to the experiment, three 19 mm diameter retroreflective markers were placed over the subject's hip, knee, and ankle joints. Additionally, eight surface electromyographic (EMG) electrodes (Trigno, Delsys, Natick, MA) were placed over the muscle bellies of the vastus medialis (VM), rectus femoris (RF), medial hamstring (MH), and lateral hamstring (LH) according to the established guidelines (www.seniam.org) (Ranganathan and Krishnan, 2012; Ranganathan et al., 2016). The EMG electrodes were tightly secured to the skin using self-adhesive tapes and cotton elastic bandages. The quality of the EMG signals was visually inspected to ensure that the electrodes were appropriately placed. After which, two inertial measurement units (IMUs) (Opal sensors, APDM, Inc., Portland, OR) were secured to the dorsum of both feet, which were used to minimize bias and objectively measure the overground gait speed of the subject prior to and after training. We chose to place the IMUs on the feet as opposed to ankle, as prior research has indicated that foot configuration is more accurate for measuring gait velocity (Washabaugh et al., 2017). The subject then performed two 3-second maximum voluntary contractions (MVCs) of their knee extensors and flexors in a seated position against a manually imposed resistance (Krishnan et al., 2013; Washabaugh et al., 2016). The peak EMG activities (i.e., the maximum of the two trials) obtained during the maximum contractions were used to normalize the EMG data obtained during walking.

The experiment consisted of three phases: (1) pre-test phase, (2) training phase, and (3) post-test phase. During the *pre-test phase*, the subject's baseline overground walking speed and hip and knee gait kinematics were established. The 10-m walk test (10MWT) was used to evaluate the baseline walking speed. The 10MWT is a psychometrically robust measure of

walking and mobility (Lin et al., 2010), and has excellent test-retest reliability ($ICC > 0.9$) (Lewek and Randall, 2011; Washabaugh et al., 2017). The subject performed three trials of the 10MWT at their self-selected pace and the average of the three trials was used in the analysis. The subject then walked on a motorized treadmill (Woodway USA, Waukesha, WI) with their hands placed over a custom-built treadmill rail system. After a 2-minute warm-up period, baseline kinematic data were recorded for one minute.

During the *training phase*, the subject first wore the resistive brace and walked over the treadmill at their comfortable walking speed without any resistance (no resistance – NR) for one minute. After which, the resistive properties of the device were adjusted based on the subject's self-reported ability and comfort level—i.e., resistance was set as the maximum comfortable resistance that the subject could walk with for the duration of the 5-minute block and was adjusted based on their feedback (forces on average were ~12% of their body-weight) (Wu et al., 2012; Yen et al., 2012). The subject then performed four 5-minute blocks of resisted walking while simultaneously attempting to match their foot trajectory to a template foot trajectory that was projected on a computer monitor placed in front of them for visual feedback. The template was created by scaling (10%–30% based on their ability) the ensemble average of their baseline hip/knee kinematics. This was performed to minimize stiff-knee gait and ensure that the subject was bending their hip and knee adequately during resisted walking (Krishnan et al., 2013; Washabaugh et al., 2016). Our previous research has shown that this type of training is effective in engaging the hamstring muscles (Washabaugh et al., 2016) and promotes locomotor recovery after stroke (Krishnan et al., 2012). The foot trajectory refers to the x - y position (X_a and Y_a) of lateral malleolus with respect to the subject's greater trochanter in the sagittal plane, and was computed using a forward-kinematic model that used hip (θ_h) and knee (θ_k) joint angles and the segment lengths of the thigh (l_1) and shank (l_2) (Krishnan et al., 2015; Saner et al., 2017; Washabaugh et al., 2016).

$$\begin{bmatrix} X_a \\ Y_a \end{bmatrix} = \begin{bmatrix} \sin\theta_h & -\sin(\theta_k - \theta_h) \\ -\cos\theta_h & -\cos(\theta_k - \theta_h) \end{bmatrix} \begin{bmatrix} l_1 \\ l_2 \end{bmatrix}$$

During the *post-test phase*, the brace was removed and the subject's overground walking speed and hip and knee gait kinematics were recorded again in an identical fashion to those during the *pre-test phase*.

Data Analysis

The device's effect on muscle activation patterns was evaluated using the EMG data collected during treadmill walking with and without resistance. The raw EMG data were band-pass filtered (20–500 Hz), rectified, and smoothed using a zero phase-lag low-pass Butterworth digital filter (8th order, 6 Hz Cut-off) (Krishnan et al., 2013; Washabaugh et al., 2016). The resulting EMG profiles were normalized to MVC data and ensemble averaged across strides using gait events generated from the accelerometer of the Trigno EMG sensors. The ensemble averaged EMG data were then divided into two bins corresponding to the stance and swing phases of gait, and the peak EMG activity was computed during each

phase. The device's effect on Locomotor adaptations and aftereffects to resistance during walking was evaluated by comparing the changes in hip/knee kinematics (first 30 strides) and overground walking speed before and after the training.

Statistical Analysis

All statistical analyses were performed using SPSS for windows version 22.0 (SPSS Inc., Chicago, IL, USA). Wilcoxon signed-rank test was used to examine the effect of the device on subjects' muscle activation during the stance and swing phases of the gait—EMG data were compared between the no resistance trial (training NR) and final training trial (training block 4). Wilcoxon signed-rank test was also used to compare differences in hip and knee excursions and overground walking speed between pre-test and post-test walking trials. Spearman's rank correlation test was used to determine if changes in hamstring muscle activation during training ($EMG_{\text{block 4}} - EMG_{\text{NR}}$) were related to the kinematic aftereffects induced by the training ($Kinematics_{\text{post-BW}} - Kinematics_{\text{pre-BW}}$). A significance level of $\alpha = 0.05$ was used for all statistical analyses and all tests were two-sided.

Results

The muscle activation profiles during robotic-resisted treadmill walking are provided in Fig. 3. Robotic-resisted treadmill walking significantly increased EMG activity of the vastus medialis ($p = 0.028$), medial hamstring ($p = 0.028$) and lateral hamstring ($p = 0.028$) muscles during the swing phase of the gait. Wilcoxon signed-rank test also indicated that 20 minutes of resisted walking significantly increased the hip ($2.6^\circ \pm 0.6^\circ$, $p = 0.028$; Fig. 4) and knee ($6.4^\circ \pm 1.4^\circ$, $p = 0.028$; Fig. 4) joint excursions and overground gait velocity (0.05 ± 0.01 m/s, $p = 0.028$) of stroke survivors. Spearman's rank correlation test indicated a significant positive correlation between increase in hamstring muscle activation and kinematic aftereffects ($\rho = 0.89$, $p = 0.017$) at the knee, but not at the hip ($\rho = 0.53$, $p = 0.277$).

Discussion

This study pilot-tested the acute effects of robotic-resisted treadmill walking with a novel wearable knee brace on kinematics, muscle activation patterns, and gait velocity of stroke survivors. The results of this study indicate that robotic-resisted treadmill walking significantly increased the EMG activity of several of the key gait muscles during walking. Most notably, the hamstring muscles, which were the primary muscles targeted during training, showed almost 5- to 7-fold increase in muscle activity. The increase in hamstring activity was also paralleled by significant improvements in hip and knee gait kinematics and overground gait velocity—a consistent finding that was observed in all the subjects ($n = 6$) tested in this study. These results provide preliminary evidence supporting that resisted walking with our robotic knee brace induces meaningful biomechanical aftereffects that translate to overground walking, making it a feasible approach to improving locomotor functions after stroke.

A growing body of evidence indicates that robotic-resisted gait training improves the locomotor ability of individuals with various neurological conditions (e.g., stroke, cerebral

palsy, and spinal cord injury) (Lam et al., 2015; Wu et al., 2014b; Wu et al., 2012; Wu et al., 2011). The basic premise underlying this approach is that the functional benefits of strength training (e.g., gait function) are augmented when combined with task-specific training, and the combination may facilitate motor learning and neural plasticity (Kleim and Jones, 2008; Lam et al., 2006; Lam et al., 2015; Wu et al., 2012). When provided through a robotic interface, this training has the benefit of flexibility through the robotic controls (i.e., resistive forcefields can be easily scaled and redirected to be patient-specific based on deficits). However, robot based systems often utilize active actuators/motors to provide resistance—making them bulky, limited to use on a treadmill, and too expensive to be used in most rehabilitation settings (small clinic and home based). For these reasons, therapists often sacrifice controllability in order to cut costs and apply resistance using ankle weights or resistance bands (Lam et al., 2009), but these alternatives only allow rigid training schema (e.g., ankle weights have difficulty targeting the hamstring muscles and large resistive forces are only possible with excessively large weights). Our eddy current braking device was created as an intermediate step between active robots and their passive alternatives—offering basic control in a package that is lightweight, useable overground, and inexpensive (< \$2000). The forcefield provided by our device is very similar to how a Lokomat robot has been used to perform resistive gait training (Lam et al., 2015), but at a fraction of cost of the Lokomat (\$3K vs \$400K). Previous research indicates that the cumulative increase in gait speed after several weeks of robotic-resisted gait training is approximately 0.05–0.1 m/s (Hornby et al., 2008; Lam et al., 2015; Lam et al., 2011; Wu et al., 2014b), whereas the acute increase (i.e., within a single session) with our device was 0.05 m/s. Additionally, we saw a 5- to 7-fold increase in hamstring muscle activity with our device (that weighs only ~1.6kg) with only 1/4th of maximum possible resistance, which is several times larger than walking with an 8kg weight or Lokomat-resisted walking (Browning et al., 2007; Houldin et al., 2011; Lam et al., 2008). Critically, this increase in hamstring muscle activity was strongly associated with the kinematic aftereffects (i.e., increase in knee joint excursion) observed at the knee joint, which suggests that larger hamstring activity during resisted walking is crucial for inducing kinematic changes with training. Although our training primarily focused on the weaker hamstring muscles, we note that training can be easily customized to the quadriceps muscle group, either by incorporating a ratcheting joint into the brace or with servo control over the linear slider. Hence, low-cost passive robots such as our eddy current braking device could represent a substantial step forward in gait rehabilitation.

From a clinical standpoint, a key question that emerges is whether the improvements in hip/ knee kinematics and overground gait speed observed in this study are clinically significant. First, we note that the reported improvements were seen within a single-session of training. Thus, we anticipate that repeated training would result in cumulative benefits that are larger than those observed in the current study. Further, the changes in hip and knee joint excursions and overground gait velocity were indeed larger than the MDC values established (Perera et al., 2006; Saner et al., 2017) after accounting for the sample size of the group ($MDC_{group} = MDC_{individual}/\sqrt{n}$) (de Vet et al., 2001; Lu et al., 2008; Washabaugh et al., 2017). Most importantly, the changes observed in overground gait speed falls in the substantial meaningful change category for stroke survivors (Perera et al., 2006).

The low sample size is a key limitation of this study. However, as noted before, the positive outcomes observed in this study were very consistent across all subjects (6 out of 6) for EMG, kinematics, and gait speed, suggesting that a larger sample size would not have changed the study results. Another limitation is that we only chose moderate-to-high functioning individuals, which limits the generalizability to individuals with more severe impairments. We intentionally chose these subjects because prior research indicates that robotic-resisted training is particularly beneficial for individuals with relatively high function (Wu et al., 2012). Thus, it is likely that assistive therapy (rather than resistive therapy) may be more suitable for individuals with significant impairments. Finally, the therapeutic benefits of this device are not currently known, as this study was not designed to study the cumulative effects of training with the device. Future clinical trials will potentially inform us on the clinical potential of this device.

In summary, this study tested the immediate effects of robotic-resisted treadmill walking using a wearable knee brace on gait function in individuals with stroke. We found that training with the brace resulted in significant improvements in EMG, kinematics, and overground gait velocity. Importantly, this finding was very consistent across subjects, indicating that this type of training may have a significant clinical potential for gait training after stroke. To our knowledge, this is the first study to show that a wearable untethered robotic exoskeleton device can induce meaningful locomotor adaptations in stroke subjects, which could also potentially translate to in home or community based rehabilitation programs. However, further testing is required to verify the cumulative benefits of resistive gait training with this device.

Acknowledgments

The research reported in this publication was supported in part by the National Institutes of Health (Grant# R01-EB019834 and Grant# R21-HD092614) and by the National Science Foundation Grant No. DGE #1256260. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the funding sources.

References

- Barnett ML, Ross D, Schmidt RA, Todd B. Motor skills learning and the specificity of training principle. *Research Quarterly*. 1973; 44(4):440–447. [PubMed: 4532277]
- Browning RC, Modica JR, Kram R, Goswami A. The effects of adding mass to the legs on the energetics and biomechanics of walking. *Medicine and Science in Sports and Exercise*. 2007; 39(3): 515–525. [PubMed: 17473778]
- de Vet HC, Bouter LM, Bezemer PD, Beurskens AJ. Reproducibility and responsiveness of evaluative outcome measures. Theoretical considerations illustrated by an empirical example. *International Journal of Technology Assessment in Health Care*. 2001; 17(4):479–487. [PubMed: 11758292]
- Dobkin BH. Strategies for stroke rehabilitation. *Lancet Neurology*. 2004; 3(9):528–536. [PubMed: 15324721]
- Duclos C, Nadeau S, Bourgeois N, Bouyer L, Richards CL. Effects of walking with loads above the ankle on gait parameters of persons with hemiparesis after stroke. *Clinical Biomechanics (Bristol, Avon)*. 2014; 29(3):265–271.
- El Amki M, Baumgartner P, Bracko O, Luft AR, Wegener S. Task-Specific Motor Rehabilitation Therapy After Stroke Improves Performance in a Different Motor Task: Translational Evidence. *Transl Stroke Res*. 2017; 8(4):347–350. [PubMed: 28091936]

- Gama GL, Savin DN, Keenan T, Waller SM, Whittall J. Comparing the effects of adapting to a weight on one leg during treadmill and overground walking: A pilot study. *Gait and Posture*. 2017;59:35–39.
- Gosline AH, Hayward V. Eddy current brakes for haptic interfaces: Design, identification, and control. *IEEE/ASME Transactions On Mechatronics*. 2008; 13(6):669–677.
- Henry, FM. Specificity vs. generality in learning motor skill. Brown, RC., Kenyon, GS., editors. Englewood Cliffs, New Jersey: Prentice Hall; 1968.
- Hornby TG, Campbell DD, Kahn JH, Demott T, Moore JL, Roth HR. Enhanced gait-related improvements after therapist- versus robotic-assisted locomotor training in subjects with chronic stroke: a randomized controlled study. *Stroke*. 2008; 39(6):1786–1792. [PubMed: 18467648]
- Houldin A, Luttin K, Lam T. Locomotor adaptations and aftereffects to resistance during walking in individuals with spinal cord injury. *Journal of Neurophysiology*. 2011; 106(1):247–258. [PubMed: 21543755]
- Klarner T, Blouin JS, Carpenter MG, Lam T. Contributions to enhanced activity in rectus femoris in response to Lokomat-applied resistance. *Experimental Brain Research*. 2013; 225(1):1–10. [PubMed: 23183638]
- Kleim JA, Jones TA. Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. *Journal of Speech, Language, and Hearing Research*. 2008; 51(1):S225–239.
- Krishnan C, Ranganathan R, Dhaher YY, Rymer WZ. A pilot study on the feasibility of robot-aided leg motor training to facilitate active participation. *PloS One*. 2013; 8(10):e77370. [PubMed: 24146986]
- Krishnan C, Ranganathan R, Kantak SS, Dhaher YY, Rymer WZ. Active robotic training improves locomotor function in a stroke survivor. *Journal of Neuroengineering and Rehabilitation*. 2012:957.
- Krishnan C, Washabaugh EP, Seetharaman Y. A low cost real-time motion tracking approach using webcam technology. *Journal of Biomechanics*. 2015; 48(3):544–548. [PubMed: 25555306]
- Lam T, Anderschitz M, Dietz V. Contribution of feedback and feedforward strategies to locomotor adaptations. *Journal of Neurophysiology*. 2006; 95(2):766–773. [PubMed: 16424453]
- Lam T, Luttmann K, Houldin A, Chan C. Treadmill-based locomotor training with leg weights to enhance functional ambulation in people with chronic stroke: a pilot study. *Journal of Neurologic Physical Therapy*. 2009; 33(3):129–135. [PubMed: 19809391]
- Lam T, Pahl K, Ferguson A, Malik RN, Bkin Krassioukov A, Eng JJ. Training with robot-applied resistance in people with motor-incomplete spinal cord injury: Pilot study. *Journal of Rehabilitation Research and Development*. 2015; 52(1):113–129. [PubMed: 26230667]
- Lam T, Pahl K, Krassioukov A, Eng JJ. Using robot-applied resistance to augment body-weight-supported treadmill training in an individual with incomplete spinal cord injury. *Physical Therapy*. 2011; 91(1):143–151. [PubMed: 21127165]
- Lam T, Wirz M, Lunenburger L, Dietz V. Swing phase resistance enhances flexor muscle activity during treadmill locomotion in incomplete spinal cord injury. *Neurorehabilitation and Neural Repair*. 2008; 22(5):438–446. [PubMed: 18780879]
- Lamberti N, Straudi S, Malagoni AM, Argiro M, Felisatti M, Nardini E, Zambon C, Basaglia N, Manfredini F. Effects of low-intensity endurance and resistance training on mobility in chronic stroke survivors: a pilot randomized controlled study. *European Journal of Physical and Rehabilitation Medicine*. 2017; 53(2):228–239. [PubMed: 27626795]
- Leon D, Cortes M, Elder J, Kumru H, Laxe S, Edwards DJ, Tormos JM, Bernabeu M, Pascual-Leone A. tDCS does not enhance the effects of robot-assisted gait training in patients with subacute stroke. *Restorative Neurology and Neuroscience*. 2017; 35(4):377–384. [PubMed: 28697574]
- Lewek MD, Randall EP. Reliability of spatiotemporal asymmetry during overground walking for individuals following chronic stroke. *Journal of Neurologic Physical Therapy*. 2011; 35(3):116–121. [PubMed: 21934372]
- Lin JH, Hsu MJ, Hsu HW, Wu HC, Hsieh CL. Psychometric comparisons of 3 functional ambulation measures for patients with stroke. *Stroke*. 2010; 41(9):2021–2025. [PubMed: 20671244]

- Lu WS, Wang CH, Lin JH, Sheu CF, Hsieh CL. The minimal detectable change of the simplified stroke rehabilitation assessment of movement measure. *Journal of Rehabilitation Medicine*. 2008; 40(8):615–619. [PubMed: 19020694]
- Lund C, Dalgas U, Gronborg TK, Andersen H, Severinsen K, Riemenschneider M, Overgaard K. Balance and walking performance are improved after resistance and aerobic training in persons with chronic stroke. *Disability and Rehabilitation*. 2017:1–8.
- Manella KJ, Field-Fote EC. Modulatory effects of locomotor training on extensor spasticity in individuals with motor-incomplete spinal cord injury. *Restorative Neurology and Neuroscience*. 2013; 31(5):633–646. [PubMed: 23735314]
- Manini T, Marko M, VanArnam T, Cook S, Fernhall B, Burke J, Ploutz-Snyder L. Efficacy of resistance and task-specific exercise in older adults who modify tasks of everyday life. *Journals of Gerontology. Series A: Biological Sciences and Medical Sciences*. 2007; 62(6):616–623.
- Mehta S, Pereira S, Viana R, Mays R, McIntyre A, Janzen S, Teasell RW. Resistance training for gait speed and total distance walked during the chronic stage of stroke: a meta-analysis. *Topics in Stroke Rehabilitation*. 2012; 19(6):471–478. [PubMed: 23192712]
- Michael KM, Allen JK, Macko RF. Reduced ambulatory activity after stroke: the role of balance, gait, and cardiovascular fitness. *Archives of Physical Medicine and Rehabilitation*. 2005; 86(8):1552–1556. [PubMed: 16084807]
- Nadeau SE, Wu SS, Dobkin BH, Azen SP, Rose DK, Tilson JK, Cen SY, Duncan PW, Team LI. Effects of task-specific and impairment-based training compared with usual care on functional walking ability after inpatient stroke rehabilitation: LEAPS Trial. *Neurorehabilitation and Neural Repair*. 2013; 27(4):370–380. [PubMed: 23504552]
- Ng MM, Hill KD, Batchelor F, Burton E. Factors predicting falls and mobility outcomes in patients with stroke returning home after rehabilitation who are at risk of falling. *Archives of Physical Medicine and Rehabilitation*. 2017
- Pak S, Patten C. Strengthening to promote functional recovery poststroke: an evidence-based review. *Topics in Stroke Rehabilitation*. 2008; 15(3):177–199. [PubMed: 18647724]
- Park BS, Kim MY, Lee LK, Yang SM, Lee WD, Noh JW, Shin YS, Kim JH, Lee JU, Kwak TY, Lee TH, Kim JY, Park J, Kim J. The effects of a progressive resistance training program on walking ability in patients after stroke: a pilot study. *Journal of Physical Therapy Science*. 2015; 27(9): 2837–2840. [PubMed: 26504305]
- Perera S, Mody SH, Woodman RC, Studenski SA. Meaningful change and responsiveness in common physical performance measures in older adults. *Journal of the American Geriatrics Society*. 2006; 54(5):743–749. [PubMed: 16696738]
- Polese JC, Ada L, Dean CM, Nascimento LR, Teixeira-Salmela LF. Treadmill training is effective for ambulatory adults with stroke: a systematic review. *Journal of Physiotherapy*. 2013; 59(2):73–80. [PubMed: 23663792]
- Proteau L, Marteniuk RG, Levesque L. A sensorimotor basis for motor learning: evidence indicating specificity of practice. *Quarterly Journal of Experimental Psychology. A: Human Experimental Psychology*. 1992; 44(3):557–575. [PubMed: 1631322]
- Ranganathan R, Krishnan C. Extracting synergies in gait: using EMG variability to evaluate control strategies. *Journal of Neurophysiology*. 2012; 108(5):1537–1544. [PubMed: 22723678]
- Ranganathan R, Krishnan C, Dhaher YY, Rymer WZ. Learning new gait patterns: Exploratory muscle activity during motor learning is not predicted by motor modules. *Journal of Biomechanics*. 2016; 49(5):718–725. [PubMed: 26916510]
- Saner RJ, Washabaugh EP, Krishnan C. Reliable sagittal plane kinematic gait assessments are feasible using low-cost webcam technology. *Gait and Posture*. 2017:5619–23.
- Schmidt, RA., Lee, T. Motor control and learning. Champaign, Illinois: Human kinetics; 1988.
- Seo HG, Lee WH, Lee SH, Yi Y, Kim KD, Oh BM. Robotic-assisted gait training combined with transcranial direct current stimulation in chronic stroke patients: A pilot double-blind, randomized controlled trial. *Restorative Neurology and Neuroscience*. 2017
- Takahashi CD, Der-Yeghiaian L, Le V, Motiwala RR, Cramer SC. Robot-based hand motor therapy after stroke. *Brain*. 2008; 131(Pt 2):425–437. [PubMed: 18156154]

- Teasell RW, Bhogal SK, Foley NC, Speechley MR. Gait retraining post stroke. *Topics in Stroke Rehabilitation*. 2003; 10(2):34–65.
- Vahlberg B, Cederholm T, Lindmark B, Zetterberg L, Hellstrom K. Short-term and long-term effects of a progressive resistance and balance exercise program in individuals with chronic stroke: a randomized controlled trial. *Disability and Rehabilitation*. 2017; 39(16):1615–1622. [PubMed: 27415645]
- Visintin M, Barbeau H, Korner-Bitensky N, Mayo NE. A new approach to retrain gait in stroke patients through body weight support and treadmill stimulation. *Stroke*. 1998; 29(6):1122–1128. [PubMed: 9626282]
- Washabaugh EP, Claflin ES, Gillespie RB, Krishnan C. A Novel Application of Eddy Current Braking for Functional Strength Training During Gait. *Annals of Biomedical Engineering*. 2016; 44(9): 2760–2773. [PubMed: 26817456]
- Washabaugh EP, Kalyanaraman T, Adamczyk PG, Claflin ES, Krishnan C. Validity and repeatability of inertial measurement units for measuring gait parameters. *Gait and Posture*. 2017:5587–93.
- Williams G, Kahn M, Randall A. Strength training for walking in neurologic rehabilitation is not task specific: a focused review. *American Journal of Physical Medicine and Rehabilitation*. 2014; 93(6):511–522. [PubMed: 24508930]
- Wu, M., Kim, J., Arora, P., Gaebler-Spira, DJ., Zhang, Y. Locomotor training through a 3D cable-driven robotic system for walking function in children with cerebral palsy: a pilot study. *Conference Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society*; 2014a. 20143529–3532
- Wu M, Landry JM, Kim J, Schmit BD, Yen SC, Macdonald J. Robotic resistance/assistance training improves locomotor function in individuals poststroke: a randomized controlled study. *Archives of Physical Medicine and Rehabilitation*. 2014b; 95(5):799–806. [PubMed: 24440365]
- Wu M, Landry JM, Schmit BD, Hornby TG, Yen SC. Robotic resistance treadmill training improves locomotor function in human spinal cord injury: a pilot study. *Archives of Physical Medicine and Rehabilitation*. 2012; 93(5):782–789. [PubMed: 22459697]
- Wu, M., Landry, JM., Yen, SC., Schmit, BD., Hornby, TG., Rafferty, M. A novel cable-driven robotic training improves locomotor function in individuals post-stroke. *Conference Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society*; 2011. 20118539–8542
- Yen SC, Schmit BD, Landry JM, Roth H, Wu M. Locomotor adaptation to resistance during treadmill training transfers to overground walking in human SCI. *Experimental Brain Research*. 2012; 216(3):473–482. [PubMed: 22108702]

Fig. 1.

(a) Schematic showing the basis of resistive torque generation in an eddy current brake. As the disc rotates through a magnetic field (B) with angular velocity (ω), eddy currents (I) form within the disc. This results in a resistive force that always opposes the angular velocity. The resulting resistance τ is also dependent on the conductivity of the disc material σ , area of the disc exposed to the magnetic field A , the thickness of the disc d , the magnitude of the magnetic field strength B , the effective radius of the disc R , and the angular velocity of the disc rotation ω (b) Computer-aided design rendering of the eddy current brake. (c) A close-up view of the knee brace embedded with eddy current brake.

Fig. 2.
Schematic of the experimental protocol.

Fig. 3.

Traces showing the mean ensemble averaged EMG activation profiles (across all subjects) of each muscle during no resistance walking and the final (4th) block of resisted walking. Bars next to the traces show the peak activation of the respective muscle during the stance and swing phases of the gait. Error bars indicate the standard error of the mean.

Fig. 4. Traces showing the mean ensemble averaged (first 30 strides) sagittal plane hip and knee joint angles (across all subjects) before and after 20-minutes of robotic-resisted walking.