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Repeat Exposure to Leg Swing Perturbations During Treadmill Training Induces Long-Term Retention of Increased Step Length in Human SCI: A Pilot Randomized Controlled Study

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Abstract

Objective

To determine whether repeat exposure to force perturbations during treadmill training can induce long-term retention of improved step length and overall improvements in locomotor function in persons with spinal cord injury.

Design

Fourteen patients with spinal cord injury were recruited and randomly assigned to swing resistance or swing assistance training groups. A controlled swing resistance or assistance force, for resistance or assistance training groups, respectively, was applied to both legs through a cable-driven robotic system during treadmill training. Each participant trained 3 times per week for 6 weeks. Step length, walking speed, 6-minute walking distance, and other clinical assessments were evaluated before and after 6 weeks of training and 8 weeks after the end of training.

Results

A significant increase in step length was observed after 6 weeks of resistance training ($P = 0.04$). Step length tended to increase after assistance treadmill training, but the change was not significant ($P = 0.18$). The changes in step length and functional gains had no significant difference between 2 groups.

Conclusions

Repeat exposure to swing resistance during treadmill training may induce a prolonged retention of increased step length, although it remains unclear whether swing resistance versus assistance is more effective in inducing increased step length.

Key Words

Locomotion, Spinal Cord Injury, Force Perturbation, Treadmill Training, Motor Adaptation

In people with incomplete spinal cord injury (SCI), locomotion is impaired because of several factors. These include paralysis, discoordination, and spasms, resulting in a substantially reduced gait speed and considerable difficulty with ambulation.[1] In general, successful locomotor recovery after SCI seems to depend on the availability of residual descending commands as well as maximizing the neural plasticity of spinal and supraspinal locomotor networks.[2,3]

Body weight–supported treadmill training (BWSTT) is a promising rehabilitation method to improve motor function and ambulation in people with SCI.[4–9] Whereas BWSTT has been shown to provide statistically significant improvements in locomotor ability and motor function for some patients,[10] the functional gains are relatively small.[11] In addition, one limitation of BWSTT is that it requires substantial involvement on the part of physical therapists. Body weight–supported treadmill training is a labor-intensive task for physical therapists, particularly for patients who require substantial walking assistance. Current robotic BWSTT is effective in reducing therapist labor during locomotor training, but it results in limited gains in walking function for some patients with SCI owing to the functional limitations of the systems.[12] As a consequence, there is a need for improving the efficacy of robotic BWSTT.

The reduced gait speed of these patients may be due to being able to take only a shorter step length and smaller step frequency during walking. For instance, depending on the severity of injury, the average step length of patients with SCI is only 0.2 m to 0.5 m,[13,14] which is approximately 30% to 75% of step length of healthy controls (ie, 0.65 m).[15] Thus, improvement in step length may induce increases in gait speed and timed walking distance of patients with SCI.

A recent study showed that an error-augmentation training paradigm–enhanced arm recovery in individuals after a stroke.[16] Thus, we speculated that error augmentation also would facilitate motor learning during locomotor training in persons with SCI. By applying a force perturbation to the leg during treadmill walking, recent studies have indicated that patients with SCI adapt to the resistance load applied to leg during treadmill walking and demonstrate an aftereffect consisting of an increase in step length after load release.[17,18] However, locomotor adaptation and the aftereffects are generally short lived, that is, the increase in step length returns to baseline within 10s of steps during the postadaptation period, after one session of force perturbation training, which may have limited clinical impact on walking function. A recent study using a split-belt treadmill paradigm indicated that prolonged repeated exposure to split-belt perturbation induces a long-term retention of improved step length symmetry in individuals after a stroke.[19] Thus, we postulated that a prolonged repeated exposure to swing resistance perturbations during treadmill training might also induce long-term retention of improved step length of persons with SCI.

The ultimate goal of robotic treadmill training for persons with SCI is successful ambulation in the home and community. Thus, the motor skills obtained from robotic treadmill training need to be effectively transferred to “real world” overground walking. Previous studies indicated that motor adaptation during treadmill walking could be partially transferred to overground walking, suggesting partial overlap of neural circuits for controlling locomotion during treadmill and overground walking.[18,20] Thus, a combined training paradigm that includes overground walking practice immediately after robotic treadmill training may be helpful in facilitating transfer of the motor skills obtained during treadmill training to overground walking.

The primary objective of this study was to determine whether repeated exposure to a leg swing resistance perturbation during treadmill training induces prolonged retention of improved step length. The second objective was to test an overall improvement in locomotor function after robotic assistance/resistance treadmill training paired with overground walking practice.

METHODS

Subjects

Screening evaluations were performed on 56 subjects, and 14 subjects with motor incomplete spinal cord injury (ie, American Spinal Injury Association Impairment Scale (AIS) Impairment Scale Level of C or D) were recruited into this study (Table 1). Inclusion criteria for participation included (*a*) age between 18 and 65 years; (*b*) history of incomplete SCI more than 1 year; (*c*) medically stable with medical clearance to participate; (*d*) level of SCI lesion between C1 and T10; (*e*) passive range of motion of both legs within functional limits of ambulation (ie, ankle dorsiflexion to neutral position, knee flexion from 0 to 120 degrees, and hip to 90-degree flexion and 10-degree extension); (*f*) ability to ambulate overground with/without assistive devices as necessary, and with orthotics that do not cross the knee; (*g*) walking with impaired walking function, that is, self-selected walking speed was less than 1.0 m/s.

Exclusion criteria included (*a*) the presence of unhealed decubiti, existing infection, severe cardiovascular and pulmonary disease; (*b*) concomitant additional central or peripheral neurological injury (eg, traumatic head injury or peripheral nerve damage in lower limbs); (*c*) history of recurrent fractures; (*d*) known orthopedic injury to the lower extremities; (*e*) other progressive diseases that affect locomotor function. All subjects currently receiving pharmacological treatment for depression and/or spasticity were included but were requested to maintain the same dosage amount during the course of intervention and follow-up periods. All subjects required medical clearance for participation, that is, the primary physician of each subject was contacted to obtain a permission to participate in this study. All procedures were approved by the institutional review board of the medical school of Northwestern University. Written informed consent was obtained from all subjects.

Apparatus

A custom-designed cable-driven robotic gait training system, CaLT, which has been reported previously,[21] was used to provide controlled bilateral resistance or assistance load, depending on group assignment, to the leg at the ankle of subjects during treadmill training. In brief, the cable-driven robotic gait training system consists of 4 nylon-coated stainless steel cables (1.6 mm), driven by 4 motors (AKM33H, Kollmorgen, Drive amplifier, Servostar 30661; two of them were located at the front of treadmill (Woodway, Waukesha, WI) and two of them were located at the back of treadmill) and cable spools affixed to custom braces that are strapped to the shank above the ankle to provide controlled resistance or assistance loads at targeted phases of gait during treadmill training. The operator controls the robotic system via a user interface that is programmed in LabVIEW (National Instruments, Austin, TX). Subject safety was ensured by software protection, an accessible panic switch and monitoring by a physical therapist with knowledge of the robotic system at all times during gait training. The ankle trajectory signals were measured using 2 sets of custom-designed 3-dimensional position detectors.[18] These position signals were used to calculate the ankle trajectory and were used to trigger loading. The adaptive control algorithm was designed for a resistance or assistance load[21] for subjects who were assigned to the resistance or assistance training groups, respectively. The magnitude of the load was determined based on the tolerance of subjects. The loads were applied to the legs from late stance (approximately 10% gait cycle before toe off) to mid-swing.

Training Protocol

A 6-week randomized robotic resistance/assistance treadmill training was conducted by licensed physical therapists (J.M.L., J.K., and J.M.) with 3 assessments of gait to determine the training effects. All the training and evaluation sessions were conducted in the research center of a rehabilitation hospital. Subjects were blocked by gait speed into slow (<0.5 m/s) or fast (≥0.5 m/s) and randomly assigned to 1 of 2 groups with resistance or assistance training. The randomization was conducted by research physical therapists through concealed envelopes, which was chosen by each subject to determine which group he or she was assigned. For each training session, subjects were fitted with an overhead harness attached to a counterweight support system. Body weight support was only provided in the instance that a counterweight was necessary to prohibit knee buckling or toe dragging during stepping. Treadmill speed was consistent with the subject's maximum comfortable walking speed, determined on the treadmill at the beginning of each training session. Subjects were allowed to wear their own shoes or orthoses during training. Training was performed 3 times per week for 6 weeks, with the training time for each visit set to 45 minutes (35 minutes of treadmill followed by 10 minutes of overground walking practice) as tolerated, excluding setup time, although short sitting breaks (approximately 1–3 minutes) were allowed. Subjects walked on a hallway at their self-selected comfortable speed during overground walking practice. Short sitting breaks were allowed as necessary. No body weight support and/or leg assistance was provided during overground walking practice, although a therapy belt was attached at the waist for protection only. The rating of perceived exertion[22] was monitored during the course of training, and the targeted rating of perceived exertion was 12 to 16.

Outcome Measures

Assessment of outcome measures was performed before, after 6 weeks of treadmill training, and 8 weeks after the cessation of treadmill training. Primary outcomes included step length, gait speed, and endurance. Specifically, self-selected and fast walking speeds were assessed using a 10-m instrumented walkway (ie, the GaitMat II, Equitest, Chalfont, PA), which has been validated in persons with SCI.[23] Step length was obtained using the software associated with the GaitMat recording system. The 6-minute timed walking distance was used to assess endurance,[24] which has been validated in persons with SCI.[23] Orthoses were allowed during 10-m and 6-minute walking tests, but subjects were required to keep consistent across before, after, and follow-up assessments. Subjects were required to keep the same assistive device during 10-m and 6-minute walking tests across all evaluation sessions.

Secondary Outcomes

Muscle tone, or spasticity, of the knee joint muscle groups was assessed using the Modified Ashworth Scale (0–4).[25] Balance was assessed using the Berg Balance Scale (BBS),[26] a clinical measure of postural stability during specific standing tasks and has been validated in persons with SCI.[27] Lower-extremity motor scores were also assessed for both lower extremities.[28] Maximum voluntary isometric joint torques of the hip, knee, and ankle joints were tested using a 6–degree-of-freedom load cell, which was affixed to the output axis of the motor of a Biodex rehabilitation/testing system. Four trials were collected for each joint and data from the last 3 trials were averaged (the first trial was used as a prepractice). In addition, scores on the Activities-Specific Balance Confidence scale[29] and changes in quality of life as measured by the 36-item Short-Form Health Survey were also assessed.[30]

Data Analysis

Data from all subjects were analyzed using scores from before and after 6 weeks of training, and 8 weeks after the end of training. Only data from subjects who completed all training and evaluation sessions were used for analysis. Independent sample *t* tests were used to compare baseline characteristics of resistance and assistant groups. Step length and walking speeds were analyzed using repeated-measures analyses of variance (ANOVAs) for the effect of training (before vs after training). Six-minute walking distance was analyzed using Friedman test (nonparametric statistical test was used for data with nonnormal distribution) for the effect of training (before vs after training). Improvement in balance (ie, BBS) and other clinical assessments were also analyzed using repeated-measures ANOVAs. Isometric peak torques of hip, knee, and ankle joints were averaged across both legs. The rate of torque development was calculated for the isometric test using the torque increase from 20% to 80% peak torque divided by the time intervals to generate this torque increase. Functional gains obtained after resistance and assistance load training were also compared using ANOVAs. Significance was noted at $P < 0.05$ for all analysis. If the ANOVA revealed significant differences, Tukey-Kramer post hoc tests were used to identify specific differences, again with significance noted at $P < 0.05$.

RESULTS

Fourteen subjects with incomplete SCI were recruited, and 12 subjects completed 6 weeks of robotic treadmill training, with 2 subjects dropping out of the study (attrition rate was 14%; from September 2010 to August 2012; Table 1). One of them was unable to complete training secondary to difficulty with transportation, and another was unable to tolerate treadmill training with the applied swing resistance load. Six subjects in the resistance training group and 6 subjects in the assistance training group completed all the 18 training sessions and 3 evaluation sessions (Fig. 1).

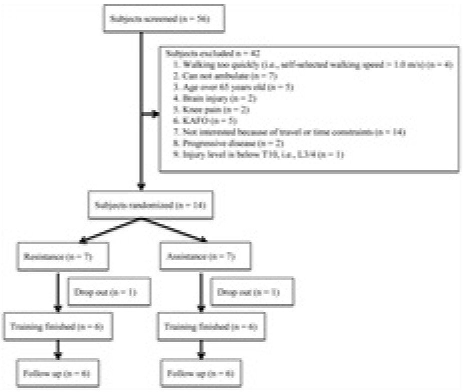

FIGURE 1: Subjects screened, enrolled, and tested. KAFO, knee-ankle-foot orthosis.

There was no significant difference between the 2 groups in age and time after injury of subjects (Table 2). Baseline measures from the resistance and assistance groups were not significantly different (Table 2).

The mean treadmill training speed and treadmill walking distance significantly increased during the course of 18 training sessions for both the resistance and assistance training groups (*P* < 0.001 for both groups, ANOVA), but there was no significant difference with regard to average treadmill training speed (*P* = 0.99) and walking distance (*P* = 0.21) between the 2 groups. The mean peak force applied to legs for swing resistance was significantly less than that for swing assistance during treadmill training (12.08 ± 2.92 N vs 25.17 ± 8.61 N for resistance and assistance groups, respectively; *P* = 0.03 < 0.05). There was no significant difference between the level of training intensity (*P* = 0.34) and overground walking practice time (*P* = 1.0) between the 2 groups. Overground walking distance significantly increased during the course of training for both groups (*P* = 0.01 and *P* = 0.002 for resistance and assistance training groups, respectively). The mean distance for overground walking training was significantly greater for the resistance group (343.9 ± 86.5 m per session) than the assistance group (198.0 ± 76.4 m per session; *P* = 0.02). No body weight support was provided for all subjects from the resistance training group, although body weight support was provided for 3 subjects from the assistance training group with the mean body weight support of the 3 subjects of 18.7% ± 4.6% and 13.3% ± 9.2% at sessions 1 and 18, respectively.

Step length of subjects significantly increased after resistance training but not after assistance training. Specifically, the mean step length of subjects from the resistance group significantly increased from 0.45 ± 0.09 to 0.49 ± 0.07 m after 6 weeks of training; *P* = 0.04 < 0.05 (Fig. 2A). Similarly, the mean step length of subjects from the assistance group tended to increase from 0.47 ± 0.04 to 0.51 ± 0.07 m after 6 weeks of training, although this was not significant: *P* = 0.18 (Fig. 2B). The changes in step length had no significant difference between the 2 groups (*P* = 0.86). The mean step lengths were 0.49 ± 0.05 m (baseline vs follow-up, *P* = 0.12) and 0.51 ± 0.06 m (baseline vs follow-up, *P* = 0.17) for resistance and assistance training groups, respectively, at 8 weeks after the end of training. Six-minute walking distance significantly increased after resistance training (*P* = 0.04). Post hoc test indicated significant difference between baseline versus follow-up test (*P* = 0.03), although there was no significant difference between baseline and after the test (*P* = 0.24). Six-minute walking distance tended to increase after assistance training, but this was not significant (*P* = 0.08; Table 3).

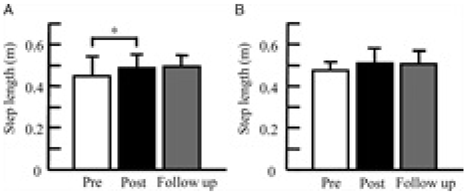

FIGURE 2: Average of step length during self-selected walking before and after 6 weeks of robotic swing resistance (A), and swing assistance (B), treadmill training, and 8 weeks after the end of training in persons with SCI. Three trials were tested and averaged across each test sessions and averaged across subjects for each group. *Significant difference, *P* < 0.05.

No significant difference occurred in functional gains between the resistance and assistance training groups after 6 weeks of robotic treadmill training and overground walking practice. Specifically, the changes in self-selected walking speed were not significantly different between the 2 groups after resistance and assistance training (*P* = 0.37), and at the 8-week follow-up (*P* = 0.90; Fig. 3A). The gain in self-selected walking speed exceeded the minimal clinically important difference (ie, ≥0.05 m/s) of patients with SCI.[31] The changes in fast walking speed were not significantly different between the 2 groups after resistance and assistance training ($P = 0.61$) and at the 8-week follow-up ($P = 0.43$). In addition, the changes in 6-minute walking distance were not significantly different between the 2 groups after resistance and assistance training ($P = 0.78$) and at the 8-week follow-up ($P = 0.84$; Fig. 3B). The gain in 6-minute walking distance was less than the minimal clinically important difference of individuals with chronic obstructive lung disease (ie, >54 m,[32] and is unknown for patients with SCI[31]).

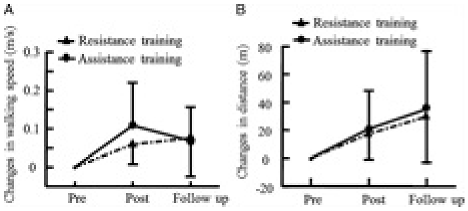

FIGURE 3: Changes in self-selected overground walking speed. A, Six-minute walking distance. B, Before and after 6 weeks of robotic swing assistance and resistance training, and 8 weeks after the end of training. Data were averaged across subjects in each group.

TABLE 1: Subject information indicating age, injury level, AIS grade, years since injury, etiology, WISCI scores, sex, assistive device/brace, ambulation level, and medication the subjects were prescribed at the time of the study

No.	Sex	Age (yr)	Level of Injury	AIS	Time After Injury	Traumatic or Nontraumatic Injury	Assistive Device/Braces	Ambulation	WISCI	Antispastic Medication
A1	M	51	C7	D	18 y 10 m	Traumatic (MVA)	Straight cane/None	PWC	19	Baclofen pump
A2	F	40	T10	D	6 y 1 m	Spinal cord tumor and tethered spinal cord	Wheel walker/None	PWC	13	Baclofen (20 mg*3) and Zanaflex (2 mg*4)
A3	M	62	C4	D	6 y 5 m	Traumatic (diving accident)	Crutches/None	PWC	19	None
A4	F	65	T9-10	D	8 y 4 m	Blood clot in spinal cord	Crutches/None	WC	16	Baclofen (20 mg*3)
A5	M	48	C5-7	D	14 y 10 m	Traumatic (motorcycle accident)	None	Walking	20	None
A6	M	59	C3-4	D	6 y 3 m	Disc herniation and spinal stenosis	Walker/None	PWC	13	Baclofen (10 mg*2)
*A7	M	47	C4-7	D	8 y 5 m	Traumatic (MVA)	Straight cane/None	Walking	20	None
R1	M	54	C6	D	9 y 7 m	Traumatic (MVA)	None	Walking	20	None
R2	M	52	C2-3	D	3 y 4 m	Traumatic (cycling accident)	Crutches/None	Walking	16	None
R3	M	39	C4	D	6 y 1 m	Traumatic (gunshot wound)	Straight cane/None	Walking	20	None
R4	M	49	C6-7	D	4 y 3 m	Traumatic (motorcycle accident)	Straight cane/None	WC	19	Baclofen (20 mg)
R5	F	51	C4-6	D	24 y 4 m	Traumatic (MVA)	None	Walking	20	None
*R6	F	63	C7	C	22 y	Traumatic (MVA)	Walker/AFO	WC	6	None
R7	M	47	C4-5	D	1 y 1 m	Transverse myelitis	Walker/AFO	WC	15	Baclofen (20 mg)

*Subject dropped out.

A, assistance group; AFO, ankle-foot orthosis; AIS, American Spinal Cord Injury Association Impairment scale; F, female; M, male; MVA, motor vehicle accident; R, resistance group; WISCI, walking index for spinal cord injury.

TABLE 2: Walking function at baseline for the resistance and assistance groups

	Resistance	Assistance	*P*
Subject age, years	50.7 ± 7.3	53.1 ± 9.1	0.59
Time post injury, years	10.1 ± 9.3	9.2 ± 5.8	0.82
SSV at baseline, m/s	0.58 ± 0.21	0.49 ± 0.17	0.45
Step length during SSV at baseline, m	0.45 ± 0.09	0.47 ± 0.04	0.56
FV at baseline, m/s	0.78 ± 0.30	0.73 ± 0.29	0.79
Step length during FV at baseline, m	0.51 ± 0.10	0.55 ± 0.07	0.40

Six-minute distance at baseline, m	202.2 ± 59.9	136.7 ± 60.0	0.09
BBS	45.3 ± 2.7	34.0 ± 10.1	0.05
LEMS	39.0 ± 5.4	41.3 ± 3.4	0.33
ABC	56.2 ± 24.5	52.0 ± 20.6	0.76
SF-36 score			
PCS	37.4 ± 7.1	38.1 ± 7.1	0.78
MCS	55.3 ± 6.4	58.1 ± 11.1	0.61
MAS	1.1 ± 0.6	1.4 ± 1.1	0.57

ABC, Activities-Specific Balance Confidence Scale; FV, fast velocity; LEMS, Lower Extremity Motor Scores; MAS, Modified Ashworth Scale; MCS, mental component summary; PCS, physical component summary; SF-36, MOS 36-item short-form health survey; SSV, self-selected velocity.

TABLE 3: Gait speeds and other clinical outcome measures pre, post 6 weeks of robotic assistance or resistance treadmill training, and 8 weeks after the end of training

		Resistance					Assistance		
	Pre	Post	FU	*p*		Pre	Post	FU	*p*
SSV (m/s)	0.58 ± 0.21	0.64 ± 0.18	0.66 ± 0.18	0.07		0.49 ± 0.17	0.60 ± 0.18	0.56 ± 0.17	0.07
FV (m/s)	0.78 ± 0.30	0.83 ± 0.19	0.88 ± 0.22	0.17		0.73 ± 0.29	0.82 ± 0.30	0.77 ± 0.31	0.01
Distance (m)	202.2 ±59.9	219.4 ± 54.6	232.1 ±52.8	0.04		136.7 ±60.0	157.9 ± 44.7	171.9 ±66.8	0.08
BBS	45.3 ± 2.7	46.8 ± 3.1	46.7 ± 4.1	0.22		34.0 ± 10.1	35.5 ± 11.4	35.5 ± 12.7	0.35
LEMS	39.0 ± 5.4	39.8 ± 4.4	40.2 ± 5.4	0.35		41.3 ± 3.4	41.7 ± 4.1	41.7 ± 3.5	0.84
ABC	56.2 ± 24.5	61.7 ± 16.2	61.7 ± 17.8	0.44		52.0 ± 20.6	52.5 ± 18.9	53.7 ± 23.0	0.91
SF-36 score									
PCS	37.4 ± 7.1	38.7 ± 5.5	36.0 ± 6.1	0.38		38.1 ± 7.1	36.8 ± 7.1	36.6 ± 9.1	0.65
MCS	55.3 ± 6.4	57.6 ± 5.3	53.8 ± 11.5	0.43		58.1 ± 11.1	59.6 ± 10.1	55.0 ± 10.0	0.23
MAS	1.1 ± 0.6	0.9 ± 0.6	1.0 ± 0.8	0.60		1.4 ± 1.1	1.4 ± 0.7	1.2 ± 0.8	0.52

ABC, Activities-Specific Balance Confidence Scale; FV, fast velocity; LEMS, Lower Extremity Motor Scores; MAS, Modified Ashworth Scale; MCS, mental component summary; PCS, physical component summary; SF-36, MOS 36-item short-form health survey; SSV, self-selected velocity.

Other clinical outcome measures, including BBS, Activities-Specific Balance Confidence Scale, lower-extremity motor scores, 36-item Short-Form Health Survey, and Modified Ashworth Scale had modest changes after treadmill training for both the resistance and assistance training groups (Table 3). Muscle strength, including peak torque, rate of torque development, and torque impulse, had no significant changes ($P > 0.05$) after treadmill training for both the resistance and assistance training group. No adverse effects were noted, although 3 subjects reported an increased tone and spasticity with treadmill training.

DISCUSSION

Applying swing resistance force to legs may augment leg kinematic errors during treadmill training in persons with SCI. Furthermore, repeated exposure to a swing resistance load applied to the legs during treadmill training may induce an accumulated effect of increased step length. Robotic treadmill training (with swing resistance or assistance) followed by immediate overground walking practice may facilitate transfer of motor skills obtained from treadmill training to overground walking, resulting in improvements in walking function in persons with incomplete SCI. Improvements in walking function were partially retained at 8 weeks after the end of robotic training, suggesting a clinical significance of this type of training paradigm. On the other hand, applying a swing assistance force to the leg may facilitate leg swing during treadmill training, which may improve overground walking through use-dependent motor learning mechanisms. There was no significant difference in walking functional gains after robotic swing resistance versus assistance training, suggesting that both error augmentation and use-dependent motor learning mechanisms may be useful in improving locomotor function in persons with SCI.

Repeated exposure to swing resistance may induce an accumulated effect of increased step length in persons with SCI. Previous studies indicated that persons with SCI adapt to a swing resistance load applied to the leg during treadmill walking and show an aftereffect consisting of increased step length after load release.[17,18] The cerebellum is suggested to be a key structure involved in error-based motor learning mechanisms during locomotor adaptation, although many other regions of the brain and spinal cord may also be involved.[33,34] Motor adaptation and the associated aftereffect are generally short-lived, which does not have much clinical significance, after one session of resistance treadmill training. However, repeated adaptation to a swing resistance load and the de-adaptation process over a longer period of time, such as 18 training sessions in this case, may induce a prolonged retention of increased step length of persons with SCI through an operant reinforcement motor learning process.[35] Overground walking practice right after swing resistance treadmill training, during which subjects may take a longer step length after load release, at least for a short period of time, may further reinforce the improved walking pattern, resulting in a longer retention time of increased step length of persons with SCI after swing resistance treadmill training. The improvement in step length of persons with SCI may induce an improvement in walking function, such as increases in walking speed and walking distance within 6 minutes.

On the other hand, a use-dependent motor learning mechanism may be involved in the condition of swing assistance treadmill training.[36] In this case, the step length increased directly owing to the swing assistance force applied to leg, instead of through a locomotor adaptation, during treadmill training. The repetition of stepping with an increased step length over 18 training sessions may induce use-dependent neural plasticity.[36] This repeated increase in step length may be further reinforced through the additional overground walking practice occurring after swing assistance treadmill training. As a result, we observed a trend of increasing step length (compared to baseline values) in persons with SCI after swing assistance treadmill training, although these changes were not significant owing to the small sample size ($P = 0.18$).

Although a previous study indicated that preserved leg muscle strength may predict changes in walking speed after locomotor training in persons with SCI,[37] changes in leg muscle strength were not related to gains in walking speed obtained after treadmill training. Similarly, we observed no significant change in muscle strength after swing resistance/assistance treadmill training, although we observed significant changes in walking speed and endurance after robotic treadmill training. A possible reason for modest changes in leg muscle strength after training may be the smaller training session (18 sessions in this case) and lower training intensity used in the current robotic treadmill training paradigm. Thus, we postulate that other factors, such as improved motor control and/or coordination (eg, electromyography (EMG) activity bursts at the appropriate time), may provide the primary contribution to the improvements in walking function in persons with SCI after robotic resistance/assistance treadmill training.

Results from the current study may have clinical applications. For instance, the results suggested that a force perturbation–based training paradigm may induce comparable functional gains in overground walking in persons with SCI as compared with swing assistance treadmill training. The functional gains obtained in the current study are comparable to or even greater than gains obtained with other robotic gait systems. For instance, in a randomized controlled study, robotic treadmill training with a fixed trajectory did not induce a significant increase in walking speed in persons with SCI (ie, 0.01 ± 0.05 m/s),[12] although results from another study indicated that the use of robotic treadmill training may significantly improve walking speeds in persons with SCI (ie, 0.11 ± 0.11 m/s).[7] Thus, a force perturbation training paradigm (ie, swing resistance) may be used as an adjunctive training strategy for improving locomotor function in persons with SCI.

This study has many limitations. The sample size was small owing to challenges of subject recruitment and financial constraints, making this a pilot study that warrants further research involving a larger cohort. All subjects in our study could ambulate with/without assistive devices and all subjects had a chronic (>1 year) spinal cord injury. We do not know whether this type of paradigm could be beneficial for subjects with a lower walking function or subjects with acute or subacute SCI. Six subjects took antispasticity medication (ie, baclofen) during the period of robotic intervention, which may potentially affect walking function in persons with SCI,[38] although we only observed a modest change in spasticity after robotic swing resistance/assistance treadmill training. The injury level of subjects ranged from C2 to T10, although most subjects (10 of 12) who finished all the training and evaluation sessions had an injury at the cervical level. We have no conclusion about the impact of injury level on the walking functional gains observed after robotic treadmill training owing to the small sample size. We had no control group who received treadmill training only without resistance or assistance force in this study. Further study with treadmill only as a control group is warranted. Body weight support was provided for 3 subjects from the swing assistance training group to prevent knee buckling or toe dragging as necessary. Subjects were allowed to hold onto the frontal or side rails for safety, and 6 subjects had experience with this robotic device in a previous study before their participation in current study, which might have also affected the results, although there was a washout period (ranged from 3 months to 22 months, which is relatively short) between the previous study and the current study. The variation in time post injury of subjects participated in this study was large, that is, ranged from 1 year and 1 month to 24 years and 4 months. However, all subjects recruited in this study were patients with chronic SCI (ie, more than 1year after SCI), for whom a natural spontaneous recovery of locomotor function might have reached a plateau. Thus, the variation in time after injury might not systematically influence the results of this study. We did not normalize the step length to the height of subjects in this study, which is consistent with previous studies,[13,39] because the difference in height of subjects tested was small (ie, mean height, 1.76 ± 0.08 m), and the results with/without normalization of step length were similar.

CONCLUSIONS

Repeated exposure to a swing resistance load during treadmill training may induce an accumulated effect of increased step length in persons with SCI, which was partially retained 8 weeks after the end of robotic treadmill training, although it remains unclear whether swing resistance is more effective than assistance in inducing increased step length in persons with SCI. Functional gains induced by swing resistance were comparable to that induced by swing assistance during treadmill training in persons with SCI, although different motor learning mechanisms may be involved during swing resistance and swing assistance treadmill training.

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Supplementary Checklist

CONSORT Checklist: http://links.lww.com/PHM/A240

Supplementary Flowchart

CONSORT Flowchart: http://links.lww.com/PHM/A239

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