Locomotor Training Approaches for Individuals with Spinal Cord Injury: A Preliminary Report of Walking-related Outcomes

Edelle C. Field-Fote, PT, PhD;[1,2] Stephen D. Lindley, MS;[2] Andrew L. Sherman, MD[3]

ABSTRACT

Background and Purpose: Body weight supported (BWS) locomotor training improves overground walking ability in individuals with motor-incomplete spinal cord injury (SCI). While there are various approaches available for locomotor training, there is no consensus regarding which of these is optimal. The purpose of this ongoing investigation is to compare outcomes associated with these different training approaches. **Subjects and Methods:** Twenty-seven subjects with chronic motor-incomplete SCI have completed training and initial and final testing at the time of this preliminary report. Subjects were randomly assigned to 1 of 4 different BWS assisted-stepping groups, including: (1) treadmill training with manual assistance (TM), (2) treadmill training with stimulation (TS), (3) overground training with stimulation (OG), or (4) treadmill training with robotic assistance (LR). Prior to and following participation we assessed walking-related outcome measures including overground walking speed, training speed, step length, and step symmetry. **Results:** Data pooled across all subject groups showed a significant effect of training on walking speed. While the differences between groups were not statistically significant, there was a trend toward greater improvement in the TS and OG groups. Post hoc subgroup analysis of outcomes from subjects with slower initial walking speed (< 0.1 m/s; n = 15) compared to those with faster initial walking speeds (≥ 0.1 m/s; n = 12) identified meaningful differences in outcomes with walking speed increasing by 85% in the slower group and by only 9% in the faster group. Step length of both stronger and weaker limb increased in all groups with the exception of those in the LR group. Step symmetry was increased in the TM and LR groups. **Discussion and Conclusion**: These results represent preliminary findings of changes in walking-related function associated with different forms of BWS locomotor training for individuals with chronic, motor-incomplete SCI. Early data indicates that locomotor outcomes in these individuals appear to be comparable across training approaches. For the individuals in this study sample, those with the greatest deficits in walking function benefitted the most from locomotor training.

Key Words: body weight support, task-specific training, walking, locomotion

INTRODUCTION

To the casual observer, the loss of lower extremity motor function and the resulting need for wheelchair use is one of the most obvious consequences of spinal cord injury (SCI). In recent years there has been a surge of interest in locomotor training for individuals with spinal cord injury. Body-weight supported (BWS) locomotor training is among the most widely used techniques. In this form of training, a harness and overhead lift assembly support a portion of the individual's body weight. This support provides an environment in which locomotor training can be initiated despite lower extremity paresis that prevents the individual from being able to fully support their body weight in standing.

Barbeau and Blunt[1] were the first to document the application of BWS treadmill training to individuals with motor-incomplete SCI (ie, having some motor function below the level of injury). Having studied locomotor function in the spinal cat model[2] in addition to having clinical background as a physical therapist, Barbeau was afforded a unique perspective. His seminal work has provided the foundation for others to further develop this approach. Since the early 1990s many other investigators, using a variety of approaches, have demonstrated that BWS locomotor training results in improvements in walking function in individuals with motor-incomplete SCI.[1,3-14] The myriad approaches available for BWS locomotor training offers the therapist many options, but leaves many unanswered questions regarding which, if any, is optimal. Further increasing the options is evidence from the neuroprosthesis literature regarding training effects with prolonged use of electrical stimulation. While ours is the only group to have published results in those with SCI[10,11] related to the combined use of these two approaches (BWS and functional electrical stimulation [FES]) for locomotor training, there is evidence from other groups that use of neuroprostheses for gait (without BWS) is associated with improved motor function even when the stimulator is turned off.[12,15-17]

In individuals with chronic (>1 year postinjury), motor-incomplete SCI in whom walking ability has been stable for some time, BWS locomotor training clearly improves walking speed and distance[1,3-14] as well as other aspects of function such as limb coordination,[10] strength,[7,8,11] muscle activation patterns,[1,13] and energy expenditure.[9] Subjectively, locomotor training in individuals with chronic, motor

---

[1]Department of Physical Therapy, [2]The Miami Project to Cure Paralysis and the Department of Rehabilitation Medicine, Miller School of Medicine, University of Miami, Miami, FL

[1]Associate Professor, Depts. of Physical Therapy and Neurological Surgery

[2]Research Associate, Dept of Neurological Surgery

[3]Dept. of Rehabilitation Medicine

incomplete SCI also improves sense of well-being.[14] However, among the investigations of locomotor training, a wide variety of training approaches and assisted-stepping protocols have been used. While investigators generally agree that the sensory inputs associated with the locomotor training protocol are important, there is little agreement regarding the optimal way to perform assisted stepping. While most investigators offer no specific details regarding how stepping is to be assisted, others[4] are proponents of highly specified manual handling techniques on the part of the therapist and still others advocate the use of neuroprosthetic[10,11] or robotic assistance.[18] Ultimately, each approach has its associated advantages and disadvantages.

The training approach which uses manual assistance of a trainer has the advantage that the experienced trainer is able to perceive the level of assistance that is needed for stepping. This allows the trainer to grade the amount of assistance that is rendered based on the individual needs of the subject over the course of each step cycle. However, this assistance may be inconsistent when applied to subjects with significant spasticity, or when the trainer becomes fatigued.

The training approach combining the use of BWS and FES has the advantage that it uses spinal reflex activity that is thought to be associated with the central pattern generator for locomotion.[19-22] As such, repeated activation of this reflex may be associated with beneficial neural changes[23-25] and may improve the synaptic efficacy of this circuit. The disadvantage of this approach is that the response to the stimulus varies both across subjects and within subject across days. While some individuals show a very robust response, others do not.

The training approach utilizing robotic-assisted locomotor training[26,27] has the advantage of allowing the subject to execute, in a highly consistent manner, the gait pattern typical of a nondisabled individual. Despite the finding that walking in the device elicits locomotor-specific EMG comparable to that observed with manual assisted training,[28] the fact remains that the device can 'walk' even in the absence of any neural activation. While there is phasic EMG activity present during walking even in subjects with motor-complete SCI,[29,30] in those with incomplete SCI this activity is much less robust when the subject does not attend to the act of walking (EFF; unpublished observation).

A training approach using overground walking has the advantage that the individual is able to train in the environment that most resembles that in which functional walking is typically performed thus facilitating transfer of training. There are distinct differences between the kinematics associated with treadmill versus overground walking.[31] As such, locomotor training over ground represents the most task-specific method to address deficits in walking function. The additional application of BWS makes use of evidence that this support allows individuals with parasis to produce more normal walking kinematics.[1] There are a number of commercially-available devices currently in clinical use that allow overground training via a mobile support system. Combining BWS with the functional electrical stimulation (FES) for dorsiflexion assist provides a task-specific approach that is relatively low cost and highly accessible. The disadvantage to this approach is that it is not possible to challenge the subject with faster walking speeds in the manner that is possible on the treadmill.

The purpose of this ongoing investigation is to assess outcomes associated with 4 different approaches to BWS locomotor training in individuals with motor-incomplete spinal cord injury. Because we routinely receive questions from physical therapists inquiring about our training methods and the 'optimal' way to perform locomotor training in individuals with incomplete SCI, we judged it appropriate to report our methods and the preliminary findings of this ongoing study. In this preliminary report, we focus on our primary outcome measures of walking-related performance including overground walking speed, training speed, step length, step symmetry with the emphasis on identifying subject characteristics that predict response to training. We hypothesized that all training approaches would be associated with improvements in walking function and would be equally effective such that there would be no significant differences in walking-related outcomes among groups. If our hypothesis is supported by the data, it would indicate that therapists have options available regarding how they may perform locomotor training for individuals with chronic incomplete SCI. They would therefore be free to make decisions regarding selection of approach based on available resources.

METHODS

Subjects: Subjects were recruited from the research subject volunteer database at The Miami Project to Cure Paralysis. To be considered for inclusion, subjects had to have: sustained spinal cord damage at least one year prior to the onset of their participation, damage at or above the level of T10, the ability to take at least one step with one leg, and the ability to rise from sitting to standing with at most moderate assistance (50% effort) of one other person. Exclusion criteria were current orthopedic problems, history of cardiac condition, presence of active hip pathology (eg, severe osteoarthritis, heterotopic ossification, etc. that could be aggravated by the training). All subjects were medically cleared by the study physiatrist (ALS) prior to participation. Twenty-seven individuals with motor-incomplete SCI have completed training to date. All subjects gave written informed consent according to the guidelines established by the Office of Human Subjects Research at the Miller School of Medicine, University of Miami.

Testing: Prior to and following training all subjects underwent a battery of tests including a short-bout (6-meter) walk and a long-bout (2-minute) walking test. For all walking-related tests, subjects were allowed to self-select their preferred walking speed as we believe this most accurately reflects the individuals' actual everyday performance. To determine the veracity of this belief we captured walking performance under 2 different conditions, a short-bout condition and a long-bout condition, as endurance might affect long-bout walking speed and we were interested in assessing whether self-selected speed differed under these 2 conditions. These 2 tests were performed within the same week but on different days.

Short-bout walking performance was captured using an 8-camera infrared system (Peak Motus™, Englewood, CO) with a 60 Hz capture rate. Subjects walked 5 times across a 10-meter instrumented walkway; subjects were allowed to rest between bouts. Short-bout walking speed and step parameters were extracted from data captured within the central 6 meters of the walkway. Long-bout walking speed was determined based on video records of the subjects as they walked for 2 minutes around an 24.4m (80-foot) oblong track. In both cases, subjects used the assistive device(s) and/or orthotic device(s) with which they were most familiar, no BWS or stimulation was used during the testing sessions.

Step length and step length ratio were evaluated based on kinematic data. The 5 longest steps for each lower extremity were used for these analyses. The step lengths were normalized to leg length of the individual subject. Leg length was measured by adding the segmental lengths of the thigh, shank, and the distance from the malleoli to the floor during stance. The measurements were taken from the marker over the lateral malleoli and the distance between the 2 malleoli during the double support phase of gait was calculated as the step length of the leading leg. The step length ratio (stronger/weaker leg) gives an indication of the bilateral step symmetry during walking. Step ratio values closer to 1.0 (ie, perfect symmetry) indicate greater symmetry in lower extremity step length during limb advancement. This ratio takes into account only the symmetry between the lower extremities and does not take into account any changes in distance that one or both legs made over the course of training. The stronger and weaker lower extremity were identified by pretraining lower extremity motor scores (LEMS).[32] These scores represent the sum of the scores from the manual muscle test values of the 5 muscle lower extremity muscle groups included in the motor assessment guidelines of the American Spinal Injury Association (ASIA).[33]

In addition to the walking-related outcome measures, as part of this ongoing investigation, data is collected to assess changes in the kinematics and kinetics of walking metabolic function, muscle activation patterns, spinal cord reflexes and their modulation, pulmonary function, balance, and perception of quality of life; the results of these analyses will be presented in ensuing reports.

Training groups: Subjects were assigned to 1 of 4 different training groups using a stratified random design based on their pretraining LEMS, as prior investigations in our lab[11] and others[32,34,35] have demonstrated a correlation between lower extremity motor scores (LEMS) and walking function. Locomotor training groups were: (1) BWS treadmill training with manual assistance (TM), (2) BWS treadmill training with peroneal nerve stimulation (TS), (3) BWS overground training with peroneal nerve stimulation (WalkAide2™, Hanger Orthopedic Group, Inc., Bethesda, Md; OG), or (4) BWS treadmill training with robotic assistance (Lokomat‘ Hocoma AG, Zurich, Switzerland; LR).

General Training Methods

For all training groups, body weight support was provided with the goal of imposing maximum lower extremity weight bearing load. Excessive knee flexion during stance phase (ie, > ~40º) or toe dragging during swing phase were indicators that BWS was insufficient and cued the trainer(s) to increase the amount of support. The level of BWS was therefore adjusted within and between sessions as needed based on these criteria. However, BWS was maintained at or below 30% as this level of support has been shown to be associated with gait kinematics that resemble walking without support[36] and higher levels of support in the overground condition are associated with subjects having difficulty moving their center of mass over their base of support.[11] Subjects in all groups were allotted a 60-minute intervention for each training day, with setup and take-down consuming an average of 10 to 15 minutes of this allotted time. Subjects were scheduled to train 5 days/week for 12 weeks.

Subjects trained on the treadmill were encouraged to swing their arms and were discouraged from weightbearing through the upper extremities, however, as in the methods described by Hornby et al[27] they were allowed to use the handrails for balance as needed. All subjects assigned to treadmill-based training groups were encouraged to walk at their maximum possible speed[4,37,38] without regard for the duration of their walking bouts. At the start of each session, speed was increased to the level at which stepping quality began to degrade (eg, toe dragging or inadequate knee flexion during swing phase, inadequate knee extension at initial stance phase, etc). Speed was then reduced to the level at which step quality was acceptable and the subject was allowed to walk at this speed. After 1 to 2 minutes at this speed, the subject was challenged by incrementing the treadmill speed upwards by 0.32 km/hr (0.2 miles/hr). After the subject completed 10 steps at this higher speed, the speed was returned to the prior level. Once the subject recovered from the faster bout, the speed was again increased until the subject could complete 20 steps at the faster speed. This sequence was continued until the subject was comfortable with the new higher speed. Speed was increased in this manner until a speed was reached at which further increases were associated with a degradation of step quality. For the OG group, subjects were encouraged to walk as fast as possible around an 80-foot track. Subjects in the LR group were progressed in their training speed using a predetermined progression algorithm. LR training was initiated at treadmill speed of 2.6 km/hr (1.6 miles/hr); treadmill speed was increased by 0.16 km/hr (0.1mile/hr) each week with a goal of reaching the maximum Lokomat speed of 3.2 km/hr (2 miles/hr) by week 5 of training. Over the course of LR training, BWS was adjusted to allow the subject to accommodate to the predetermined speed. All subjects were allowed to rest as needed during the training sessions.

Group-specific Techniques for Assisted Stepping

Subjects in the TM group received assistance for stepping based on guidelines recommended by Behrman and Harkema;[4] unilateral or bilateral manual assistance was provided as required by the subject. The goal of the assistance was to assist the subject to execute a step that approached normal kinematics; the trainers' hand placement was directed to the flexor or extensor surface of the stepping limb as appropriate to the step phase. Subjects in the TS group received bilateral stimulation (Digitimer Ltd, Hertfordshire, UK) to the common peroneal nerve according to procedures we have used in prior studies.[10,11] The guidelines we used for placement of the bipolar electrodes are given in Table 1. The anode placement was determined by the site associated with the most robust flexion withdrawal response to stimulation. Stimulation parameters were 300-600 ms train, 50 Hz, 5 – 20mA. Current and electrode placement were adjusted to elicit a robust flexion withdrawal response (ankle dorsiflexion with hip and knee flexion); when necessary, stimulation parameters (pulse duration, train duration, current) were adjusted during the training session to manage habituation. The stimulation was manually triggered by the trainer to coincide with the onset of stepping.

Subjects in the OG group were allowed to use the upper extremity assistive device with which they were most comfortable as well as lower extremity orthotic devices. No attempt was made to progress subject to more challenging assistive devices over the course of training. Subjects in the LR group walked in the robotic gait orthosis, the subject was secured to the robotic orthosis with straps at the trunk, pelvis, and bilateral lower extremities. Specifics related to the mechanics of the device are described elsewhere.[28]

Data Analysis

Statistical analyses were performed using the General Linear Model (GLM; SPSS, Inc., Chicago, Ill) to assess overall differences in walking speed due to training, where there were differences among groups (or trends toward differences) post hoc testing was done using Bonferroni multiple comparison to identify differences between specific groups or paired t-tests test to assess differences within groups. The relationship between short- and long-bout walking speed was assessed using Pearson's *r* statistic, the relationship between LEMS and walking speed was assessed using Spearman's *r* statistic

RESULTS

Stratified random assignment to training group resulted in the following subject distribution among training groups: TM = 7, TS = 7, OG = 7, LR = 6. Subject demographic information is given in Table 2. The number (mean [SD]) of training sessions over the 12-week training duration was 44.5 [8; range = 27 – 54].

Overground Walking Speed and Training Speed

Overall short-bout walking speed increased from 0.11 [0.09]m/s to 0.14 [0.12]m/s and long-bout speed increased from 0.11 [0.08]m/s to 0.14 [0.11]. The large standard deviation reflects the large range of subject performance. Overall, training was associated with a 55% increase [range = -59% to +417%] in short-bout walking speed and a 37% increase [range = -38% to +203%] in long-bout speed. The overall effect of training (data collapsed across group) was significant for short-bout walking speed test [F(1,23) = 14.72, *P* = 0.001; power = 0.96], with a trend suggesting differences among groups [F(3,23) = 2.387, *P* = .095; power = 0.52]. Power analysis[39] based on these data indicated that there is a moderate effect of training (*ES* = 0.49) and that while there is a trend toward differences among groups, 13 subjects will be required per group (total 52) to observe between-group differences with at an alpha level of 0.05 with 80% power. Given, the trend toward between-group differences, we opted to pursue post-hoc analyses on these data.

Post hoc testing with paired t-tests showed significant differences in pre- to post-training short-bout walking speed in both the TS group (*P* = 0.02) and the OG group (*P* = 0.008), while differences were not observed in the TM

Table 1

Cathode position	Anode Position	Pulse width	Train duration	Voltage or current	Comments
1-2 cm distal to fibular head	1-2 cm proximal to popliteal fossa, lateral to midline	0.3 – 1 ms pulse duration	250 – 500 ms	As determined by response and patient tolerance	Robust response that is typically well tolerated
As above	Medial tibial plateau	As above	As above	As above	Often a less robust response relative to site above, but easier to elicit in some individuals
As above	5 – 8 cm distal to cathode	As above	As above	As above	Least likely to elicit hip & knee flexion, but produces robust dorsiflexion
Medial aspect of plantar arch	Medial dorsal surface of foot	As above	As above	As above	Robust response, but may be poorly tolerated due to compression inside shoes

Table 2

Group	Subject ID	Age	Gender	Chronicity (yrs)	Level of Injury*	Initial LEMS	Training sessions
TM	TM1	22	M	1.1	C3	40	41
	TM2	45	M	5.1	C6	26	45
	TM3	63	M	1.0	C6	31	47
	TM4	50	F	2.8	C5	26	30
	TM5	21	M	1.1	C6	11	40
	TM6	60	M	5.8	C6	17	53
	TM7	23	M	4.8	C6	24	54
Mean		**41**		**3.1**			**44.3**
Median					**C6**	**26**	**45**
TS	TS1	50	M	1.4	T2	25	53
	TS2	49	M	10.3	C6	31	31
	TS3	40	F	18.7	C5	25	34
	TS4	37	M	10.2	T4	31	48
	TS5	27	M	1.3	T5	14	50
	TS6	43	M	1.1	C5	38	46
	TS7	40	F	19.8	C5	25	51
Mean		**41**		**9.0**			**44.7**
Median					**C6**	**25**	**48**
OG	OG1	46	M 3	.4	C5	27	42
	OG2	37	M	2.8	C5	25	47
	OG3	41	M	2.8	C4	36	30
	OG4	64	M	2.8	C3	32	49
	OG5	49	M	11.3	C6	18	48
	OG6	41	M	4.1	C6	29	52
	OG7	59	F	2.0	T4	34	45
Mean		**48**		**4.2**			**44.7**
Median					**C5**	**29**	**47**
LR	LR1	37	M	1.8	T7	14	54
	LR2	56	F	10.0	T2	19	40
	LR3	33	M	11.4	C6	23	42
	LR4	44	M	1.0	T10	26	27
	LR5	40	M	4.4	C4	24	50
	LR6	49	M	23.4	C5	30	52
Mean		**43.2**		**8.7**			**44.2**
Median					**C6**	**23.5**	**46**

group ($p = 0.09$) and LR group ($P = 0.47$). The overall effect of training was significant for the long-bout test [F(1,19) = 8.39, $P = 0.009$; power = 0.78], but there was no observable differences among training groups in long-bout speed [F(3,19) = 0.125, $P = 0.944$]. Group-wise data for the initial and final speeds for the short- and long-bout walking test are given in Figures 1 – 2, respectively. There was a significant correlation between initial short- and long-bout speeds ($r = 0.724$, $P < .001$) and between final short- and long-bout speeds ($r = 0.703$, $P = .001$).

There was a significant increase in training speed [F(1, 23) = 68.302, $P < .001$; power = 1.0], with significant differences among the training groups [F(3,23) = 7.137, $P = .001$; power = 0.959]. Overall, study participants experience a 123% increase [range = -0.2% to +544%] in training speed. There were also significant differences in training speed among the training groups [F(3,23) = 7.137, $P = .001$]. Bonferroni post hoc multiple comparison test indicated that the training speed for the OG was significantly slower than for all the other groups ($P \leq 0.005$ for all groups), there were no significant differences in training speed among the treadmill-based training groups. Group-wise data for the initial and final training speeds are given in Figure 3.

Examination of the data indicated that there was a notable difference in outcomes between the subgroups of subjects having initial walking speeds of less than 0.10m/s (slower subgroup; n = 15) and those with initial walking speeds of 0.10m/s or greater (faster subgroup; n = 12). Initial and final short-bout walking speeds for each of these subgroups are given in Table 3. While there were an insufficient number of subjects to allow statistical analyses, the descriptive statistics indicate that the slower subgroup demonstrated a more marked increase in walking speed than did the faster subgroup. The short-bout walking speed for this group increased from a mean of 0.04m/s (range = 0.0 – 0.09) to 0.08 m/s (range = 0.0 - .25) reflecting an 85% increase. This improvement was greater than that observed in the faster subgroup whose speed increased from 0.20 m/s (range = 0.1 – 0.43) to 0.22 m/s (range = 0.05 – 0.52), reflecting a 9.2% increase. The range of speed increases for the subgroup of subjects with slower walking speeds was 57% (LR group) to 106% (TS group), while the range of speed changes for the faster subgroup ranged from –19% (LR group) to 35% (OG group). These differences are illustrated in Figure 4. Finally, there was a positive correlation between initial LEMS and initial walking speed ($r_s = 0.37$, $P = 0.05$). The outcomes were similar for the long-bout walking speed (data not shown).

Step length and step symmetry

In 3 of the 4 training groups the length of the step was increased in both the weaker and stronger legs; in most

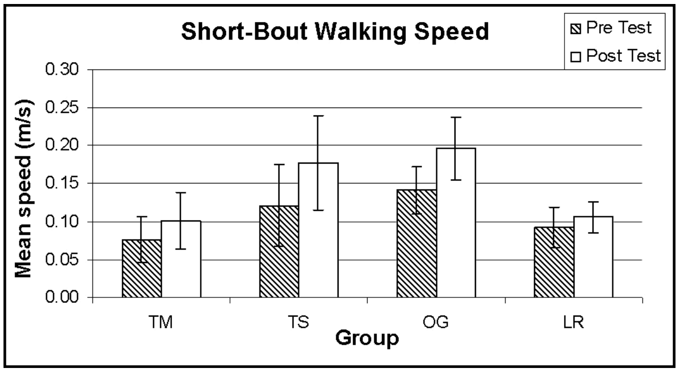

Figure 1. Pre- (striped bars) and post-training (open bars) short-bout walking speed for each of the training group. Each bar represents the mean of 5 trials captured as subjects walked across a 6-meter walkway. Error bars represent the standard error of the mean.

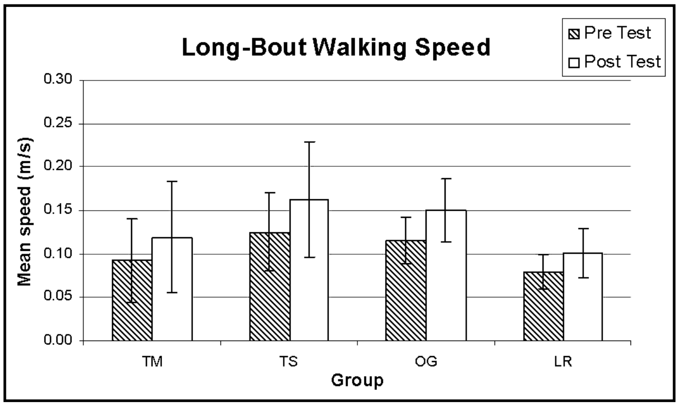

Figure 2. Pre- (striped bars) and post-training (open bars) short-bout walking speed for each of the training group. Each bar represents data from video record of the subjects as they walked around an 80-foot (24.4m) walkway. Error bars represent the standard error of the mean.

cases the weaker leg exhibited a slightly greater increase in step length than did the stronger leg (Figure 5). The TM group increased step length in the stronger lower extremity by 11%, while the weaker lower extremity increased by 24%. The TS group increased by 20% and 22% in the stronger and weaker lower extremity, respectively. The OG group showed a slightly greater increase in the stronger leg than the weaker leg with 30% and 27% increases, respectively. Subjects in the LR group experienced a decrease in their step length in both legs with a decrease of 1% and 22% in step length in the stronger and weaker legs, respectively.

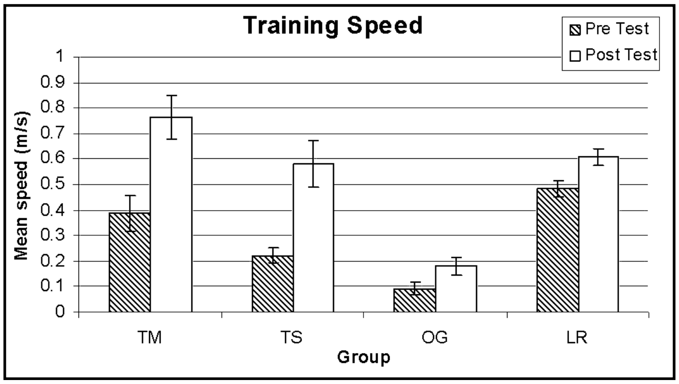

Figure 3. Initial (striped bars) and final (open bars) training speeds for each of the training groups. Error bars represent the standard error of the mean.

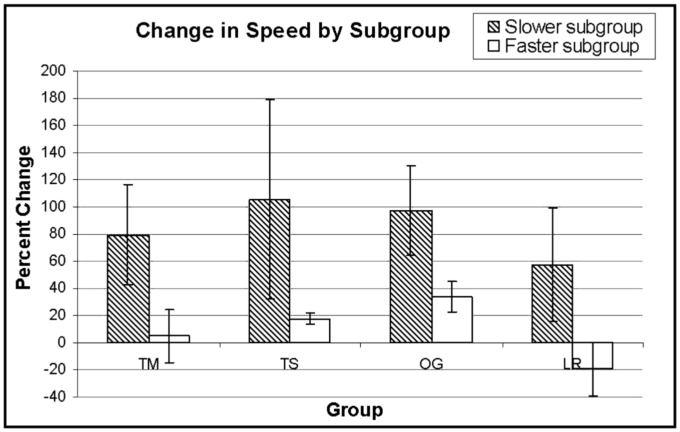

Figure 4. Percentage change in short-bout walking speed for slower (striped bars) and faster (open bars) subgroups according to training group. Error bars represent standard error of the mean.

Change in ratio of step length between the stronger and weaker leg, an indication of bilateral symmetry, varied among the training groups (Figure 6). The LR group demonstrated the most notable increase in symmetry (24%), followed by the TM group (20%). Ratio values did not change markedly for either the TS group or the OG group with change of 4% and -3% change in symmetry, although the OG group exhibited the greatest symmetry overall being the only group with symmetry values of > 0.80 both pre- and post-training.

Table 3

Approach	Subgroup	N	Initial mean speed (m/s)	Range (m/s)	Final mean speed (m/s)	Range (m/s)	% change
TM	Slower	5	0.04	0.01 - 0.08	0.07	0.01 - 0.15	80%
	Faster	3	0.17	0.10 - 0.25	0.18	0.08 - 0.29	5%
TS	Slower	5	0.06	0.02 - 0.09	0.11	0.03 - 0.25	106%
	Faster	3	0.29	0.14 - 0.43	0.34	0.15 - 0.52	17%
OG	Slower	2	0.04	0.01 - 0.08	0.08	0.01 - 0.30	97%
	Faster	5	0.18	0.13 - 0.24	0.24	0.14 - 0.33	34%
LR	Slower	3	0.05	0.02 - 0.09	0.07	0.05 - 0.10	57%
	Faster	3	0.15	0.12 - 0.16	0.12	0.05 - 0.16	-19%

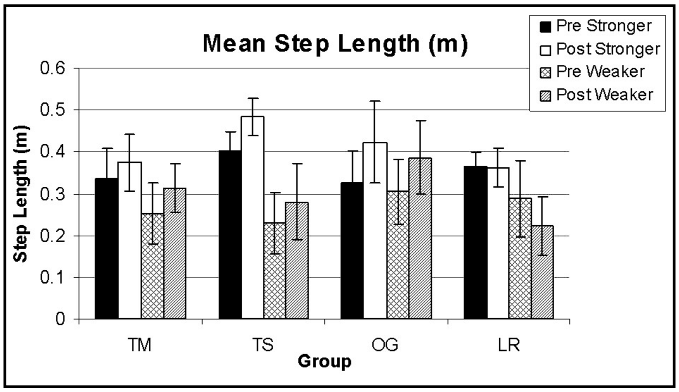

Figure 5. Pre-training step lengths for the stronger (solid bars) and weaker (crosshatched bars) lower extremity compared to post-training values for the stronger (solid bars) and weaker (striped bars) lower extremities. Strength assessment based on initial LEMS. Error bars represent standard error of the mean.

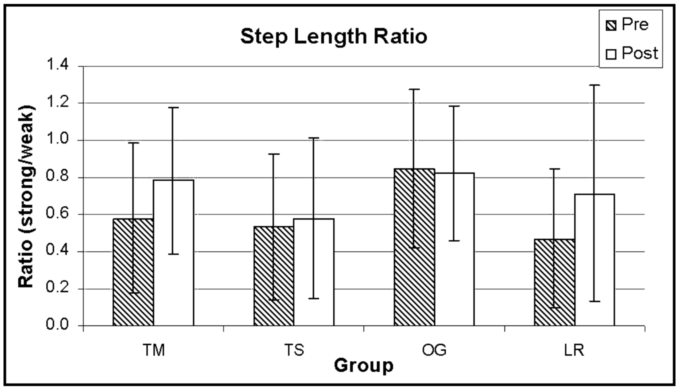

Figure 6. Pre- (striped bars) and post-training (open bars) ratio of step length in the stronger/weaker lower extremity. Values closer to 1 indicate increased bilateral step length symmetry. Error bars represent the standard error of the mean.

DISCUSSION

These preliminary results indicate that all forms of locomotor training studied are associated with improved walking performance. While to some extent the great variability among subjects *within* groups combined with the small sample size accounts for the overlap of outcomes between groups, the fact remains that there are no obvious differences *between* groups. Despite this, detailed statistical analyses suggest a trend for greater improvement in the groups that were trained using the electrical stimulation for assistance with stepping (the TS and OG approaches). While our first inference upon reviewing these data was that training approaches that use FES are optimal, a possible alternative explanation is that this is the approach with which my laboratory group is most expert. Having previously published on the approach combining BWS and FES,[10,11] we have considerably more experience with this form of training than with the other approaches. We must consider the possibility that this experience at least partly underlies the apparent superiority of these approaches as practiced in our setting.

Our analysis of subgroups based on initial walking speed, suggests that those with lower initial walking speeds are likely to experience the most marked gains in walking function, a finding that has been reported by others.[39] While these results are preliminary they represent data from 27 subjects, a sample size that is larger than most previously published studies of locomotor training. These results may further suggest that the optimal approach to locomotor training may depend on the individual's initial walking function. While there are too few subjects per subgroup for meaningful statistical analysis based on training approach, those subjects who had the slower walking speeds (<0.10 m/s) made the greatest improvement with training using the TS approach while those with faster walking speeds made the greatest improvement with training using the OG approach. Our finding regarding the lower effectiveness of LR training in individuals with better walking function are consistent with results from other groups.[39]

We would be remiss to overlook the point that while subjects made important gains in walking function, none of these subjects were able to discard their wheelchairs and become community ambulators. While there are definitions of what walking velocities constitute functional ambulation in other groups, such as individuals with stroke, there are no such definitions for spinal cord injury.[40] Cerny et al[41] suggest that individuals with paraplegia who are unable to attain walking speeds of at least 0.9m/s are unlikely to be community ambulators who use walking as their primary means of mobility. In the subject pool reported herein, none of our subjects attained speeds anywhere near this value. Despite this, subjects consistently reported that the gains made over the course of training made a meaningful difference to their daily function, enabling them to successfully perform activities that they were previously unable to do, such as access a bathroom that did not meet the requirements of the Americans with Disabilities Act, climb a flight of stairs to enter a building, or cruise around the kitchen using the countertops for support. Such outcomes are important as they represent meaningful change in function.

There were a few subjects whose walking speed was slower at the final test than it had been at the time of the initial test. For the short-bout walking test, there were 4 subjects for whom this was true; however, these subjects all walked faster during the final long-bout test than they had during final long-bout walking test. Further, there were 4 *different* subjects who walked slower during the final long-bout walking test than they had during the initial long-bout test, and these subjects all walked faster during the final short-bout test than they had during final short-bout walking test. This variability in performance suggests that it may be beneficial to perform repeated testing on different days, to obtain the most accurate assessments of the subjects' typical performance. Further, as performance is known to improve with repeated testing, an assessment of change in walking function in a comparison group that received no locomotor training would strengthen the case for change being due to the intervention. However, we feel that as subjects were in the chronic stage of injury, it is unlikely that there would be a training effect from tests administered with 12 weeks intervening between the initial and final tests.

Importance of Subject Classification

The finding, however preliminary, that subjects with different initial walking speeds may respond differently to training bear out the appeal made by Craik[29] in her 2005 McMillan address when she called for treatment directed by patient classification. In prior studies of locomotor training, there are important subject subclassifications that are often overlooked. In our opinion, the most critical of these are chronicity and level of injury. Studies of individuals with acute and subacute injury have demonstrated important improvements in walking function,[3-6] but the inherent variability among individuals in the amount of spontaneous recovery makes it difficult to determine whether the early benefits of this form of training surpass those associated with standard rehabilitation practice.[42] For this reason, some investigators interested in BWS locomotor training for individuals with SCI have restricted their study sample to individuals who are in the chronic stage (ie, ≥ 1 year postinjury) in whom the greater part of motor recovery has already occurred,[9,11] but this is not universally true. Subject data is frequently pooled to include both those with subacute injury and those with chronic injury.

Aside from the issue of injury chronicity, the issue of severity of injury also influences locomotor outcomes. A few studies[1,4,6,43] have investigated the effects of locomotor training in individuals with motor-complete injury (ie, no motor function below the level of injury) associated with severe SCI, and while results suggest that these individuals are able to generate locomotor-appropriate movement or muscle activity during walking on the treadmill, they are not able to walk overground. This should not be construed to mean that these individuals do not benefit from this training as there are many benefits to walking that go beyond the restoration of motor function. For example, we have previously demonstrated that there is a metabolic cost associated with treadmill walking in an individual with motor-complete SCI,[44] this would suggest that there may be cardiorespiratory benefits to walking for individuals with motor-complete SCI. Further, walking is likely to be associated with improved bone health, and perhaps improved pulmonary function,[45] as well as bowel motility and tissue health.[46] Despite this, functional benefits leading to improvements in overground walking are observed only in individuals with incomplete injury.

A final issue related to subject classification is level of injury. While studies of individuals with motor complete SCI appear to suggest that locomotor output is greater in those with higher levels of injury,[31] this may not be true in individuals with motor incomplete injury. Given 2 individuals with comparable severity of injury, one with cervical level injury and one with thoracic level injury, the added arm and trunk control available to the individual with thoracic level injury is likely to be the more functional of the two. Related to this is the concept of spinal cord versus spinal root damage. We include in our studies only subjects who have injury at or above T10 as the possibility for nerve root damage is greater in those with injury below T10. As such, lower motor neuron damage would be expected to be associated with decreased probability that sensory information associated with training would be effectively transmitted to the spinal cord.

Comparisons with Prior Studies

A number of investigators have studied the effect of an extended period of locomotor training in individuals with chronic, motor-incomplete SCI. These outcomes are summarized in Table 4. In the interest of analysis based on subject classification, these data are restricted, where possible, to that obtained from individuals with chronic, incomplete SCI of at least 1-year duration. There were 2 exceptions—in one case, for purposes of completeness, data is included from a subject who was 11 months postinjury.[8] In another case, in a study of 40 subjects,[17] only group data are reported and these data include 9 individuals with stroke and 2 individuals with incomplete SCI of less than one year duration. Studies related to use of neuroprosthetic assistance were included only if they contained data related to subject performance with the stimulators 'off.' These earlier outcomes are consistent with preliminary conclusion from our own data, that there are meaningful improvements in walking function regardless of the training type.

Improvements in overground walking speed vary considerably across reports even when the same training approach is used. Part of this variability is likely due to the small sample size in some studies; however, our data indicates that there is a large range of improvements in walking speed even when subjects are trained using the same technique. In the present study, the variable that differed among groups was the manner in which assistance for stepping was provided. That these findings are consistent with those of prior investigations suggests that walking-related outcomes are similar across approaches, even when all other factors are held constant. It is important to note, however, that these preliminary data refer only to walking-related outcome measures. It is possible that there may be differences in responses of other measures of function (ie, standing balance) or impairment (ie, spasticity) among the different training approaches. These will be investigated in detail when full results are available.

Same Approach, Different Protocols

Beyond issues related to different training approaches, it is important to note that different investigators use different training protocols even when using the same training approach. For example, while Wernig et al[7] and Behrman and Harkema[4] offer specific recommendations for training, other investigators make no mention of specific training protocols.[3,5,6,9,47] While there is theoretical support for many of the specific recommendations, that support is not

Table 4

Training Type	Author (primary)	N (only subjects with chronic MISCI)	Injury Level	Injury Severity (ASIA Classification)	Mean BWS During Training	Number of Training Sessions (training period)	Mean Initial Overground Walking Speed	Mean Final Overground Walking Speed	Mean Change in Overground Walking Speed
BWS & Manual assist treadmill	*Barbeau & Blunt[1]	2	C7;T8	C/D	Start: 40% End: 0%	NG (6 wks)	Unable	0.23m/s	+0.23m/s
	Barbeau et al[13]	9	C1 – L1	C/D	Start:NG End 0%	NG (6wks)	0.23 ±0.13m/s	0.44 ±0.17m/s	89%
	†Hicks et al[14]	14	C4 – L1	C: 11	Start:73% End: 20%	144 sessions (12 months)	Categorical score; median = 0	Categorical score; Median = 2-4	5 of 11 subjects increased scores
	Protas et al[9]	3	T8 – T12	C: 1 D: 2	Start: 40% End: 0%	60 (12 wks)	0.12m/s	0.32m/s	160%
	‡Wernig & Muller[8]	5	C4 – T12	C	Start: 40% End: 0%	40 - 140 (2–7 mos)	4: unable 1: 0.06m/s	0.12m/s	+0.12m/s
	Wernig et al[7]	29	NG	C	10 – 40%	15 - 100 (3-20 wks)	Categorical score = 2 out of 5	Categorical score =4 out of 5	improved by 2 categories out of 5
FES- & BWS - treadmill training	Field-Fote[11]	19	Cerv: 13 Thor: 6	C	30%	30 – 36 (12 wks)	0.12 ±0.08m/s	0.21± 0.15ms	75%
FES-assisted overground training	§Barbeau et al[12]	14	C5 – L1	C: 5 D: 9	None	Daily use (1 year) 1 – 4 channels FES	~0.46±1.2m/s	~0.78 ±1.4 m/s‡	71%
	Granat et al[15]	6	C3 – L1	C: 3 D: 3	None	Daily use (≥ 3 mos)	0.30±0.24	0.33±0.27	8%
	Ladouceur & Barbeau[16]	14	C3 – L1	C/D	None	Daily use (26 wks – yrs) 1 – 4 channels FES	0.49±0.49m/s	0.74±0.63m/s	50%
	¶Wieler et al[17]	31	C1 – T12	C/D	None	Daily use (3 mos – years) 1 channel FES	0.46± 0.06m/s	0.6± 0.09m/s	30%
Robotic assisted treadmill training	Hornby et al[27]	1	C6	C	Start: 46% End: 12%	~17 (7 wks)	0.11 ms	0.14 ms	27%
	Wirz et al[26]	20	C5 – L1	C: 9 D: 11	Start: 50% End: 30%**	24 – 40 (8 wks)	~0.37±0.9m/s	~0.48±0.9m/s	50%

NG = not given
Cerv = cervical, Thor= thoracic

*Overground walking data given for only one subject
†14 subjects total, 2 = ASIA B; 11 ASIA C subjects competed training (1 dropout). Data based on table in text
‡ One subject (of 5 subjects) was only 11 months post SCI
§ Data based on figures in text
¶ 29/40 subjects had chronic SCI, 2 had subacute SCI (<12mos) only pooled data is given

unequivocal. Regarding the use of handrails, for example, Barbeau and Blunt[1] and Visintin and Barbeau[48] suggest, based on qualitative assessments of EMG and gait quality in individuals with SCI that the use of handrails tends to degrade walking performance in those individuals who have *asymmetric* lower extremity involvement. They note that there are clear differences in response to use of parallel bars in those with gait asymmetry and those with symmetrical gait. Conversely, Conrad et al[38,49] advocate on the opposite side of the issue, promoting the use of parallel bars in order to improve stability and achieve a more normal gait pattern.

The recommendation to train at the fastest speed possible is the only protocol parameter that has been systematically tested against alternatives; and while there is evidence to suggest that training speed is important that evidence is not overwhelming. Visintin and Barbeau[48] offer observations about quality of gait and EMG with increased speed in those with SCI, but the best evidence comes from individuals with stroke rather than SCI. Pohl et al[38] in a study of individuals with stroke have demonstrated a statistically significant effect of speed in their study of individuals with stroke. Sullivan et al[37] found trends toward greater improvement in those trained at faster speed but differences were not statistically significant. The direct applicability of these findings to individuals with symmetrical lower extremity involvement due to SCI remains unclear. In the present study, subjects in the OG group were exposed to training speeds that were significantly lower than of the treadmill-based training groups. Despite this, this group demonstrated improvements in walking speed that were comparable to those trained on the treadmill. This suggests that training speed alone is not an essential factor for improving walking speed.

CONCLUSIONS

These preliminary results of the effects of locomotor training on walking-related outcome measures indicate that all of the forms of BWS-assisted locomotor training are associated with improvements in overground walking speed. These improvements in walking speed appear to be most marked in those subjects with the greatest initial impairment in walking function, providing support for the view that treatment should be directed by patient classification. Step length and step symmetry appears to be not as responsive to training in some groups compared to others. Based on these data, therapists are encouraged to use whatever forms of locomotor training they have available to improve walking speed in individuals with motor-incomplete SCI. Outcomes related to measures other than locomotor function are part of this ongoing investigation and it is likely that these may be preferentially influenced by different forms of training.

ACKNOWLEDGEMENTS

Study supported by NIH grant # HD41487 to EFF NIDRR SCI Model Systems Grant # H133N000017 by the Schumann Foundation and by The Miami Project to Cure Paralysis.

REFERENCES

[1] Barbeau H, Blunt R. A novel interactive locomotor approach using body weight support to retrain gait in spastic paretic subjects. In: Wernig A, ed. *Plasticity of Motoneuronal Connections*. New York, NY: Elsevier Science Publications; 1991:461-74.

[2] Barbeau H, Rossignol S. Recovery of locomotion after chronic spinalization in the adult cat. *Brain Res.* 1987; 412:84-95.

[3] Gardner MB, Holden MK, Leikauskas JM, Richard RL. Partial body weight support with treadmill locomotion to improve gait after incomplete spinal cord injury: a single-subject experimental design. *Phys Ther.* 1998;78: 361-374.

[4] Behrman AL, Harkema SJ. Locomotor training after human spinal cord injury: a series of case studies. *Phys Ther.* 2000;80:688-700.

[5] Dietz V, Colombo G., Jensen JL. Locomotor activity in spinal man. *Lancet.* 1994;344:1260-1263.

[6] Dietz V. Locomotor capacity of spinal cord in paraplegic patients. *Ann Neurol.* 1995;37:574-582.

[7] Wernig A. Laufband therapy based on 'rules of spinal locomotion' is effective in spinal cord injured persons. *Eur J Neurosci.* 1995;7:823-829.

[8] Wernig A. Laufband locomotion with body weight support improved walking in persons with severe spinal cord injuries. *Paraplegia.* 1992;30:229-238.

[9] Protas EJ, Holmes SA, Qureshy H, Johnson A, Lee D, Sherwood AM. Supported treadmill ambulation training after spinal cord injury: a pilot study. *Arch Phys Med Rehabil.* 2001;82:825-831.

[10] Field-Fote EC, Tepavac D. Improved intralimb coordination in people with incomplete spinal cord injury following training with body weight support and electrical stimulation. *Phys Ther.* 2002;82:707-715.

[11] Field-Fote E. Combined use of body weight support, functional electric stimulation, and treadmill training to improve walking ability in individuals with chronic incomplete spinal cord injury. *Arch Phys Med Rehabil.* 2001;82:818-824.

[12] Barbeau H, Ladouceur M, Mirbagheri MM, Kearney RE. The effect of locomotor training combined with functional electrical stimulation in chronic spinal cord injured subjects: walking and reflex studies. *Brain Res Rev.* 2002;40:274-291.

[13] Barbeau H, Danakas M, Arsenault B. The effects of locomotor training in spinal cord injured subjects: a preliminary study. *Restor Neurol Neurosci.* 1993;5:81-84.

[14] Hicks AL, Adams MM, Martin GK et al. Long-term body-weight-supported treadmill training and subsequent follow-up in persons with chronic SCI: effects on functional walking ability and measures of subjective well-being. *Spinal Cord.* 2005;43:291-298.

[15] Granat MH FAABD. The role of functional electrical stimulation in the rehabilitation of patients with incomplete spinal cord injury—observed benefits during gait studies. *Paraplegia.* 1993;31:207-215.

[16] Ladouceur M. Functional electrical stimulation-assisted walking for persons with incomplete spinal injuries: longitudinal changes in maximal overground walking speed. *Scand J Rehabil Med.* 2000;32:28-36.

[17] Wieler M, Stein RB, Ladouceur M, et al. Multicenter evaluation of electrical stimulation systems for walking. *Arch Phys Med Rehabil.* 1999;80:495-500.

[18] Colombo G, Wirz M, Dietz V. Driven gait orthosis for improvement of locomotor training in paraplegic patients. *Spinal Cord.* 2001;39:252-255.

[19] Bussel B. Late flexion reflex in paraplegic patients. Evidence for a spinal stepping generator. *Brain Res Bull.* 1989;22:53-56.

[20] Bussel B. Evidence for a spinal stepping generator in man. Electrophysiological study. *Acta Neurobiol Exp (Warsz).* 1996;56:465-468.

[21] Jankowska E, Jukes MG, Lund S, Lundberg A. The effect of DOPA on the spinal cord. 6. Half-centre organization of interneurones transmitting effects from the flexor reflex afferents. *Acta Physiol Scand.* 1967;70:389-402.

[22] Schomburg ED, Petersen N, Barajon I, Hultborn H. Flexor reflex afferents reset the step cycle during fictive locomotion in the cat. *Exp Brain Res.* 1998;122: 339-350.

[23] Fung J. Effects of conditioning cutaneomuscular stimulation on the soleus H-reflex in normal and spastic paretic subjects during walking and standing. *J Neurophysiol.* 1994;72:2090-2104.

[24] Crone C, Nielsen J, Petersen N, Ballegaard M, Hultborn H. Disynaptic reciprocal inhibition of ankle extensors in spastic patients. *Brain.* 1994;117(Part 5):1161-1168.

[25] Carnstam B. Improvement of gait following functional electrical stimulation. I. Investigations on changes in voluntary strength and proprioceptive reflexes. *Scand J Rehabil Med.* 1977;9:7-13.

[26] Wirz M, Zemon DH, Rupp R, et al. Effectiveness of automated locomotor training in patients with chronic incomplete spinal cord injury: a multicenter trial. *Arch Phys Med Rehabil.* 2005;86:672-680.

[27] Hornby TG, Zemon DH, Campbell D. Robotic-assisted, body-weight-supported treadmill training in individuals following motor incomplete spinal cord injury. *Phys Ther.* 2005;85:52-66.

[28] Colombo G, Joerg M, Schreier R, Dietz V. Treadmill training of paraplegic patients using a robotic orthosis. *J Rehabil Res Dev.* 2000;37:693-700.

[29] Craik RL. Thirty-Sixth Mary McMillan Lecture: "Never Satisfied." *Paper presented at: PT2005, Annual Conference and Exhibition of the American Physical Therapy Association.* Boston, Mass: 2005.

[30] Maegele M, Muller S, Wernig A, Edgerton VR, Harkema SJ. Recruitment of spinal motor pools during voluntary movements versus stepping after human spinal cord injury. *J Neurotrauma.* 2002;19:1217-1229.

[31] Dietz V, Nakazawa K, Wirz M, Erni T. Level of spinal cord lesion determines locomotor activity in spinal man. *Exp Brain Res.* 1999;128:405-409.

[32] Waters RL, Adkins R, Yakura J, Vigil D. Prediction of ambulatory performance based on motor scores derived from standards of the American Spinal Injury Association. *Arch Phys Med Rehabil.* 1994;75:756-760.

[33] American Spinal Injury Association. International Standards for Neurological Classification of Spinal Cord Injury. Chicago, Ill: American Spinal Injury Association; 2002.

[34] Waters RL, Adkins RH, Yakura JS, Sie I. Motor and sensory recovery following incomplete tetraplegia. *Arch Phys Med Rehabil.* 1994;75:306-311.

[35] Waters RL, Adkins R, Yakura J, Vigil D. Prediction of ambulatory performance based on motor scores derived from standards of the American Spinal Injury Association. *Arch Phys Med Rehabil.* 1994;75:756-760.

[36] Finch L. Influence of body weight support on normal human gait: development of a gait retraining strategy. *Phys Ther.* 1991;71:842-855.

[37] Sullivan KJ, Knowlton BJ, Dobkin BH. Step training with body weight support: effect of treadmill speed and practice paradigms on poststroke locomotor recovery. *Arch Phys Med Rehabil.* 2002;83:683-691.

[38] Conrad B, Benecke R, Carnehl J, et al. Pathophysiologic aspects of human locomotion. In: Desmedt JE, ed. *Motor Control Mechanisms in Health and Disease*. New York, NY: Raven Press; 1983:717-26.

[39] Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. Orlando, Fla: Academic Press, Inc; 1977.

[40] Perry J, Garrett M, Gronley JK, Mulroy SJ. Classification of walking handicap in the stroke population. *Stroke.* 1995;26:982-989.

[41] Cerny D, Waters R, Hislop H, Perry J. Walking and wheelchair energetics in persons with paraplegia. *Phys Ther.* 1980;60:133-139.

[42] Dobkin B, Apple D, Barbeau H, et al. Walking-related gains over the first 12 weeks of rehabilitation for incomplete traumatic spinal cord injury; the SCILT randomized clinical trial. *Neurologie Rehabil.* 2004;4:S15.

[43] Harkema SJ, Hurley SL, Patel UK, Requejo PS, Dobkin BH, Edgerton VR. Human lumbosacral spinal cord interprets loading during stepping. *J Neurophysiol.* 1997;77:797-811.

[44] Nash MS, Jacobs PL, Johnson BM, Field-Fote' E. Metabolic and cardiac responses to robotic-assisted locomotion in motor-complete tetraplegia: a case report. *J Spinal Cord Med.* 2004;27:78-82.

[45] Cohen MI, Beckley CD, Perez MX, Solomon NH, Field-Fote EC. Effect of locomotor training on respiratory function in individuals with incomplete cervical or thoracic spinal cord injury. *Cardiopul Phys Ther*. 2005:31.

[46] Krebs H, Volpe B, Alisen M, Hogan N. Increasing Productivity and Quality of Care: Robot-Aided Neuro-Rehabilitation. *J Rehabil Develop.* 2000;37.

[47] Dietz V. Locomotor pattern in paraplegic patients: training effects and recovery of spinal cord function. *Spinal Cord.* 1998;36:380-390.

[48] Visintin M, Barbeau H. The effects of parallel bars, body weight support and speed on the modulation of the locomotor pattern of spastic paretic gait. A preliminary communication. *Paraplegia.* 1994;32:540-553.

[49] Conrad B, Benecke R, Meinck HM. Gait disturbances in paraspastic patients. In: Delwaide PJ, Young RR, eds. *Clinical Neurophysiology in Spasticity. Vol. 1 Restorative Neurology*. Netherlands: Elsevier Science Publishers; 1985:155-74.