

Enhanced Gait-Related Improvements After Therapist- Versus Robotic-Assisted Locomotor Training in Subjects With Chronic Stroke

A Randomized Controlled Study

T. George Hornby, PhD, MPT; Donielle D. Campbell, PTA; Jennifer H. Kahn, DPT;
Tobey Demott, MPT; Jennifer L. Moore, MPT; Heidi R. Roth, MSPT

Background and Purpose—Locomotor training (LT) using a treadmill can improve walking ability over conventional rehabilitation in individuals with hemiparesis, although the personnel requirements often necessary to provide LT may limit its application. Robotic devices that provide consistent symmetrical assistance have been developed to facilitate LT, although their effectiveness in improving locomotor ability has not been well established.

Methods—Forty-eight ambulatory chronic stroke survivors stratified by severity of locomotor deficits completed a randomized controlled study on the effects of robotic- versus therapist-assisted LT. Both groups received 12 LT sessions for 30 minutes at similar speeds, with guided symmetrical locomotor assistance using a robotic orthosis versus manual facilitation from a single therapist using an assist-as-needed paradigm. Outcome measures included gait speed and symmetry, and clinical measures of activity and participation.

Results—Greater improvements in speed and single limb stance time on the impaired leg were observed in subjects who received therapist-assisted LT, with larger speed improvements in those with less severe gait deficits. Perceived rating of the effects of physical limitations on quality of life improved only in subjects with severe gait deficits who received therapist-assisted LT.

Conclusions—Therapist-assisted LT facilitates greater improvements in walking ability in ambulatory stroke survivors as compared to a similar dosage of robotic-assisted LT. (*Stroke*. 2008;39:1786-1792.)

Key Words: locomotion ■ exercise ■ robotics

Approximately 80% of individuals poststroke regain some locomotor function, although many present with significant gait deficits, including reduced gait speeds¹ and spatio-temporal abnormalities.² To improve ambulation poststroke, the use of locomotor training (LT)³ performed on a treadmill or overground has received considerable attention.⁴ Based primarily on investigations in animal models of complete spinal cord injury,⁵ LT consists of task-specific gait training which reinforces specific sensorimotor inputs associated with upright locomotion. LT has been shown to yield greater increases in locomotor ability than conventional rehabilitation protocols,^{6–8} with the extent of improvements dependent on the severity of gait deficits.^{3,9} Providing weight support during LT,¹⁰ particularly in those with greater deficits,¹¹ allows reduced but symmetrical weight bearing, which may facilitate stepping in subjects unable to bear their full weight and discourage use of compensatory strategies. Providing weight support can also allow LT at higher treadmill speeds,¹⁰

which is a critical parameter shown to facilitate locomotor recovery.^{8,9}

Despite such promising results, the efficacy of LT may be limited by the physical demand placed on therapists to manually facilitate stepping in subjects who require substantial physical assistance.^{12,13} Repetitive practice of many rehabilitation interventions including LT is mechanical in nature¹⁴ and may be amenable to automation. The use of robotic rehabilitation devices has been promoted as an alternative to therapist-assisted interventions.¹⁵ By imposing consistent symmetrical lower limb trajectories, robotic devices may provide many of the afferent cues considered critical to retraining locomotion^{16,17} while minimizing the demands on therapists.¹⁸ In severely impaired nonambulatory stroke survivors, similar or slightly greater outcomes were observed using robotic-assisted LT as compared to more conventional rehabilitation protocols,^{19–22} generating substantial enthusiasm for the clinical use of robotic devices.

Received September 18, 2007; final revision received October 17, 2007; accepted October 26, 2007.

From the Department of Physical Therapy (T.G.H.), University of Illinois at Chicago; the Sensory Motor Performance Program (T.G.H., D.D.C., J.H.K., T.D., J.L.M., H.R.R.), Rehabilitation Institute of Chicago, Ill; and the Department of Physical Medicine and Rehabilitation (T.G.H.), Northwestern University Feinberg School of Medicine, Chicago, Ill.

Correspondence to T. George Hornby, Department of Physical Therapy, University of Illinois at Chicago, 1919 W Taylor St, M/C 898, Chicago, IL 60612. E-mail tgh@uic.edu

© 2008 American Heart Association, Inc.

Stroke is available at <http://stroke.ahajournals.org>

DOI: 10.1161/STROKEAHA.107.504779

Unfortunately, robotic-assisted LT may also have several drawbacks. For example, the application of locomotor assistance using 1 commercial device, the Lokomat (Hocoma Medial Engineering Inc, Zurich) is limited to the sagittal plane, with restricted movement in the frontal and transverse planes. In the basic guidance mode of operation, robotic-assisted walking in ambulatory subjects with incomplete spinal cord injury (SCI)²³ reduced metabolic costs and hip flexor muscle activity as compared to therapist-assisted walking. When subjects were asked to maximize their efforts during robotic-assisted walking, energy expenditure was slightly reduced during robotic- versus therapist-assisted stepping, with abnormal muscle activity patterns present in the former condition. A recent study indicated that the aerobic stimulus generated during gait training has a positive response on improvements in walking ability poststroke,^{7,24} which may be limited using robotic devices.

Another drawback of robotic LT devices is the passive guidance provided during stepping. Substantial literature suggests that motor learning may be reduced during guided practice,^{25–27} particularly as compared to unconstrained or assist-as-needed paradigms, the latter of which occurs during therapist-assisted LT. Robotic-assisted LT provides rigid assistance in frontal and sagittal planes at the trunk, which reduces the muscular activity necessary to maintain postural stability during stepping. Whether therapist-assisted LT using an assist-as-needed strategy can facilitate greater improvements versus robotic-assisted LT in ambulatory stroke survivors is unclear. It is further unknown whether initial locomotor deficits influence the improvements in walking ability using robotic- or therapist-assisted LT, particularly in light of recent data indicating no difference in gait recovery in nonambulatory stroke survivors.^{20,21}

The purpose of the present study was to determine the extent of walking-related improvements obtained after therapist- versus robotic-assisted LT in individuals with severe to moderate gait dysfunction poststroke. In a prospective, randomized, controlled trial, ambulatory subjects with hemiparesis of >6 month duration were provided 12 LT sessions on a treadmill with symmetrical guidance using a robotic device (robotic-assisted LT) versus manual facilitation using a single therapist (therapist-assisted LT). We hypothesized that therapist-assisted LT, which emphasizes assistance as needed to sustain locomotion and maintain postural stability, would elicit greater gait-related improvements in ambulatory individuals poststroke.

Methods

The study was conducted over 2 years at the Rehabilitation Institute of Chicago. All procedures were approved by the Institutional Review Board. All subjects provided written informed consent.

Subjects

Subjects with hemiparesis of >6 months duration after unilateral, supratentorial, ischemic, or hemorrhage stroke were recruited. Lesion location was confirmed by radiographic findings, with no evidence of bilateral or brain stem lesions. All subjects were required to walk >10 m overground without physical assistance at speeds ≤ 0.8 m/s at their self-selected velocity (SSV), using assistive devices and bracing below the knee as needed. Exclusion criteria included: significant cardiorespiratory/metabolic disease, or other neurological or orthopedic injury that may limit exercise participa-

tion or impair locomotion; size limitations for the harness/counterweight system or robotic orthosis,²¹ no botulinum toxin therapy in the lower limbs <6 months prior to enrollment; scores <23 on the Mini Mental Status examination (MMSE)²⁸; and, subjects could not receive concurrent physical therapy. All subjects required medical clearance to participate.

A power analysis using estimates of gait speed improvements after robotic^{29,30} and therapist-assisted⁹ LT indicated that 48 subjects (24 in each group) were required for 92% power using an unpaired comparison. Subjects were enrolled until 48 individuals completed all training sessions (on-protocol analysis). Subjects were stratified according to initial gait speed; those who ambulated ≤ 0.5 m/s were classified with severe locomotor impairments and those with moderate impairments ambulated >0.5 and ≤ 0.8 m/s.^{3,9} Randomization was performed upon enrollment using sealed envelopes concealed from view.

Training Protocol

LT in both treatment groups consisted of 12 sessions (30 minutes/session) with therapist- or robotic-assistance. In both groups, subjects wore a harness attached to a counterweight system to provide body weight support. Approximately 30% to 40% of a subject's body weight was supported during the first session, and decreased in approximately 10% increments per session as tolerated without substantial knee buckling or toe drag. LT started at 2.0 kmph during the initial session, was increased by 0.5 kmph every 10 minutes as tolerated to 3.0 kmph, and remained there for subsequent visits. Blood pressure and heart rate were assessed during LT and maintained below 220/110 mm Hg and 85% of age-predicted maximum heart rate. Rest breaks were provided as necessary, with LT performed within 1 hour.

Subjects randomized to robotic-assisted LT were provided continuous symmetrical stepping assistance using the Lokomat. The design and control of this device have been described previously.²¹ With body weight support, subjects were attached to the device at the trunk, pelvis, and bilateral lower extremities with hip and knee joints aligned to computer-controlled actuators, and elastic straps were used to assist toe clearance. The robotic device provided continuous sagittal plane assistance of the hip and knee joints in trajectories approximating symmetrical reciprocal human gait. Assistance was provided during both stance and swing phases, and subjects were given continuous visual feedback of estimates of bilateral hip and knee torques during walking. Subjects were encouraged to generate maximal effort throughout training, particularly in the paretic limb. Visual feedback from a full-length mirror and verbal encouragement from therapists were also provided.

Subjects randomized to therapist-assisted LT were trained at similar weight support and speeds as the robotic-assisted group. In place of robotic assistance, a single therapist provided manual facilitation at the paretic limb to facilitate stepping. Assistance was provided only as necessary to ensure continuous walking¹⁴ as opposed to approximating normal kinematics.^{3,9} Visual feedback from a mirror and verbal encouragement were also provided. Lower extremity orthoses were removed if stepping could proceed with minimal risk of orthopedic injury.

Outcome Measures

Standardized assessments were performed before and after 12 LT sessions and at 6 months after training. Blinding of researchers who performed the assessments was not feasible secondary to personnel constraints. Primary outcome measures included gait speed during overground walking collected on an instrumented walkway which can detect spatiotemporal gait patterns (GaitMat II, Equitest Inc). During testing, subjects walked without physical assistance at their SSV and fast velocity (FV), with specific instructions to "walk at your normal, comfortable pace" and "walk as fast as safely possible", respectively. Subjects were exposed to the walkway within the week before the first testing session. Two trials at both SSV and FV were averaged separately.

Secondary measures included assessment of selected spatiotemporal gait patterns and clinical measures of activity and participation.

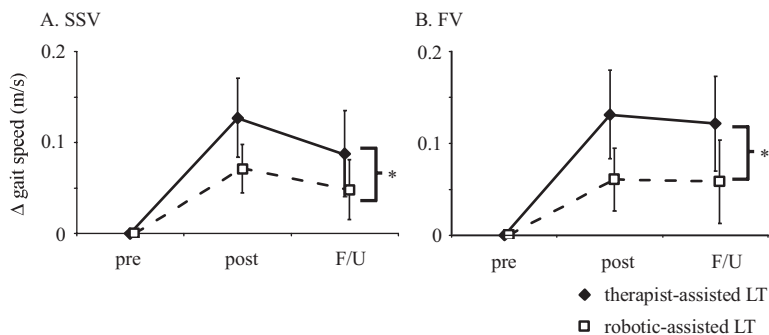


Figure. Changes in gait speed at post- and F/U assessments at self-selected velocity (SSV; A) and fast velocity (FV; B). Scores are presented for therapist-assisted LT (closed diamonds) versus robotic-assisted LT (open squares), after subtraction of pre-LT values. Asterisk (*) indicates significant main effect of treatment group.

Data acquired during SSV and FV was used to calculate single limb stance time of the impaired limb, expressed as a percentage of the gait cycle duration, with 40% considered normal.³¹ In addition, step length asymmetry is evident in persons poststroke, typically with reduced unimpaired versus impaired step length.³² Step length asymmetry was quantified as the ratio of unimpaired to impaired step length, calculated as $(100 - |100 - 100 \times (\text{unimpaired step length} / \text{impaired step length})|)$, with 100% indicating perfect symmetry (ie, all asymmetrical values are <100% with positive changes indicating improvements). Clinical measures included the 6 minute walk test at SSV, the modified Emory Functional Ambulation Profile (mEFAP),³³ and the Berg Balance Scale.³⁴ Subjective assessments included the Frenchay Activities Index³⁵ and the normative-based, physical component summary score of the Medical Outcomes Questionnaire, Short Form 36 (physical SF36).³⁵

Clinical measures of strength, spasticity, and depression were used to compare baseline impairments between groups. Strength was determined using manual muscle testing of bilateral ankle dorsi- and plantarflexors, knee flexors and extensors, and hip flexors, extensors, adductors, and abductors, using integer scores from 0 to 5.³⁶ Spasticity was assessed using Modified Ashworth scores of ankle plantarflexors, knee flexors and extensors, and hip flexors, extensors, and adductors.³⁷ Depressive symptoms were measured using the Center for Epidemiological Studies-Depression Scale.³⁵

Statistical Analysis

Baseline characteristics and training parameters were compared between treatment groups using unpaired *t* tests, Mann-Whitney U, and chi-squared comparisons as appropriate, with ratio data tested for normality. Data were analyzed using change scores from pre- to posttraining and pre- to follow-up (F/U) assessments. Only data for subjects who completed training were used; data from posttraining were entered as F/U for subjects who could not attend the final evaluation (2 subjects in both groups). All data are presented as mean \pm standard deviation in tables/text, with mean \pm 95% confidence intervals presented in the Figure. All parametric measures were analyzed using a 3-way repeated-measures ANOVA with main factors of treatment (robotic- versus therapist-assisted), severity of locomotor deficits (moderate versus severe), and repeated for time (post- versus pretraining and F/U versus pretraining). Posthoc *t* tests were performed only for significant main effects of treatment. Mann-Whitney U comparisons were performed between treatment groups and severe versus moderate gait impairment for nonparametric data, with Wilcoxon signed-ranks tests for post-pre versus F/U-pre measures. Significance was set at $\alpha=0.05$, with Bonferroni corrections made for repeated comparisons.

Results

Subject Recruitment, Demographics, and Training Characteristics

Screening evaluations were performed on 149 subjects with 62 enrolled; 17 were excluded for bilateral/brain stem lesions, 20 presented with other diagnoses which may limit LT, 8 did not meet MMSE criteria, 22 walked too quickly, 5 could not

ambulate without physical assistance, 2 were limited by size restrictions, and 13 were not interested because of travel or time constraints.

For subjects who fulfilled inclusion criteria and were randomized into treatment groups, 14 were unable to complete LT. Four subjects in robotic-assisted LT dropped; 2 discontinued secondary to leg pain during training, 1 experienced pitting edema, and 1 experienced travel limitations. Ten subjects dropped in therapist-assisted LT; 4 subjects discontinued secondary to leg pain, 1 experienced an injury outside LT, 1 reported fear of falling during training, 1 presented with significant hypertension, 1 experienced travel limitations, and 2 discontinued because of subjective exercise intolerance. The number of dropouts were not significantly different between groups ($\chi^2=2.57$; $P=0.11$).

Table 1 provides demographic characteristics and measures of impairments (ie, strength, spasticity, and depression) of patients who completed LT. There were no statistical differences in these variables before training. Specifically, there were no differences in summed or individual muscle strength scores for the paretic lower limb or in the nonparetic limb. Modified Ashworth scores were not different at any joint (plantarflexor scores shown in Table 1).

All subjects received 12 LT sessions at speeds up to 3.0 kmph with weight support decreased throughout training.

Table 1. Demographic and Baseline Characteristics of Subjects Who Completed LT

	Robotic-Assisted	Therapist-Assisted	<i>P</i> Values
Demographics			
Age, y	57 \pm 10	57 \pm 11	0.92
Gender, male/female	15/9	15/9	0.99
Race, white/other	12/12	12/12	0.99
Side of paresis, left/right	8/16	8/16	0.99
Type of stroke, isch/hem	12/12	10/14	0.56
Duration, mo	50 \pm 51	73 \pm 87	0.32
Ankle foot orthosis, n	18	12	0.27
Assistive device, n	13	12	0.84
Baseline impairments			
Muscle testing, sum	19 \pm 6.2	19 \pm 6.2	0.75
Modified Ashworth, PF	0.8 \pm 0.9	1.0 \pm 1.2	0.74
CES-D	13 \pm 9.2	9.6 \pm 8.8	0.12

Isch indicates ischemic; hem, hemorrhagic; CES-D, Center for Epidemiological Studies-Depression scale.

Table 2. Comparison of Training Parameters Between Treatment Groups

Training Parameters	Robotic-Assisted	Therapist-Assisted	<i>P</i> Values
Distance, m	1440±39	1444±51	0.14
Speed, m/s	0.80±0.02	0.81±0.01	0.01
Duration, min	29.9±0.4	29.6±0.8	0.01
Weight support, %	25±6.7	21±7.5	0.11

Mean distance, duration, weight support, and speed provided per session. Parametric comparisons made for weight support; nonparametric for speed, time, and distance.

Table 2 details the training characteristics per session between groups. Mean distance walked and amount of weight support were not different, with small but significant differences in training speed (0.01 m/s>in therapist-assisted LT) and training duration/session (18 seconds>in robotic-assisted LT) using nonparametric comparisons.

Table 3 provides mean pre-LT, post-LT, and F/U data for all primary and secondary outcome measures, with no significant differences between treatment groups for any measure before LT.

Spatiotemporal Gait Patterns—Effects of Treatment Group

Table 3 provides the probability values for the main effects of treatment and severity of locomotor impairment using the 3-way ANOVA. Analysis of primary outcome measures (gait speed) revealed a significant main effect for treatment group, with greater improvements in SSV and FV after therapist-assisted LT (Figure, A and B). Posthoc analysis of gait speed differences at SSV revealed nearly 2-fold greater improvements during therapist- versus robotic-assisted LT at post-LT

(0.13±0.11 m/s versus 0.07±0.07 m/s, respectively; *P*=0.04) and F/U (0.08±0.11 m/s versus 0.04±0.08 m/s; *P*=0.11). Consistent changes in FV were noted, with improvements of 0.13±0.12 m/s versus 0.06±0.08 (*P*=0.04) at post-LT, and 0.12±0.13 m/s versus 0.06±0.11 m/s (*P*=0.06) at F/U (Table 3). Notably, whereas there were no significant main effects for time, statistically significant differences between treatment groups were observed only at post-LT.

For secondary measures of spatiotemporal gait patterns, a significant main effect of treatment group was observed for single limb stance at FV but not SSV. Subjects who received therapist-assisted LT improved their impaired single limb stance time, whereas robotic-assisted LT resulted in very little change. Posthoc analysis revealed greater improvements at post-LT assessment (2.5±3.7% versus 0.1±0.6%, *P*<0.01), with larger but nonsignificant differences at F/U (5.6±17% versus -0.2±3.1%; *P*=0.09). No significant main effect for treatment group was observed for step length asymmetry at either SSV or FV.

Spatiotemporal Gait Patterns—Effects of Locomotor Impairment

Significant main effects for severity of locomotor deficits were also observed, with greater improvements in speed in subjects with moderate versus severe locomotor deficits (Table 3). Mean increases of 0.13±0.09 m/s was observed at the post versus pre-LT assessment in moderately impaired subjects at SSV, with 0.06±0.08 m/s gait speed increases in those with severe locomotor impairment. Consistent changes were observed at FV. Notably, there was no significant interaction between the main effects of treatment and severity of locomotor impairment in any of the variables. For step length asymmetry, greater improvements were observed in subjects with severe impairment, although only at SSV. There

Table 3. Mean Pre-, Post-LT, and F/U Data for Outcome Measures

	Robotic-Assisted			Therapist-Assisted			Treatment Effects	Severity Effects
	Pre	Post	F/U	Pre	Post	F/U		
Primary measures								
SSV, m/s	0.45±0.19	0.52±0.21	0.50±0.21	0.43±0.22	0.56±0.28	0.52±0.25	.03	.03
FV, m/s	0.59±0.30	0.65±0.32	0.66±0.34	0.60±0.33	0.73±0.39	0.72±0.38	.02	.04
Secondary measures: gait parameters								
% single limb stance: SSV	20±5.6	20±5.6	20±5.6	20±6.5	22±7.0	22±7.7	.22	.85
% single limb stance: FV	22±6.0	22±6.1	22±6.5	22±7.1	25±7.8	28±18	.03	.94
Step asymmetry: SSV	71±24	75±22	71±20	75±21	79±18	79±19	.85	.04
Step asymmetry: FV	73±23	70±26	70±17	78±22	79±17	77±18	.53	.09
Secondary measures: clinical assessments								
6-minute walk, m	170±86	186±88	193±94	170±86	204±96	203±104	.14	.13
mEFAP, s	431±380	412±366	402±368	420±474	394±469	376±414	.67	.42
Berg Balance Scale	43±10	44±10	45±10	42±10	44±11	46±8.9	.66	.45
Frenchay Activities Index	21±7.5	22±7.8	23±7.5	25±9.7	25±9.8	26±9.0	.32	.08
Physical SF36	45±8.1	44±9.8	43±8.8	41±11	45±9.4	45±9.0	.01	.04

Three-way ANOVA for change scores to analyze all parametric data, with *P* values of the main effects of treatment group (robotic- vs therapist-assisted LT) and severity of locomotor impairment (moderate vs severe). Nonparametric comparisons were made for the Berg Balance Scale and FAI, with *P* values shown for post- vs pre-LT comparisons only. Data are presented for all 24 subjects in each LT group, with *n*=23 assessed for spatiotemporal gait parameters at FV because of equipment malfunction during FV testing.

was no significant main effect of severity of locomotor impairment for single limb stance time.

Clinical Measures

For clinical measures of activity and participation, improvements were observed in both groups in almost all subjective or objective measures, with no significant effects for treatment group or severity of locomotor impairment with the exception of physical SF-36 scores. Significant main effects for treatment group and locomotor severity were observed, with greater improvement in therapist-assisted LT and those with severe locomotor impairment, with a significant interaction. Specifically, increased physical SF36 scores were observed only in subjects with severe locomotor deficits who received therapist-assisted LT, with improvements of 8.9 ± 11 at post-LT and 7.7 ± 9.8 at F/U. In contrast, mean changes in physical SF36 scores in all other subjects groups were less than <1 pt. There were no significant differences for time for any clinical measure.

Discussion

In the present study, greater improvements in overground gait speed and impaired single limb stance were observed in ambulatory stroke survivors who received therapist- versus robotic-assisted LT. Although larger changes were observed in subjects with less severe gait deficits, the lack of interaction between main factors of treatment and locomotor impairment indicates that therapist-assisted LT was superior for all chronic ambulatory subjects. Improvements in physical SF36 scores were greater only in those subjects with severe impairments who received therapist-assisted LT. The lack of significant effects for time indicates changes were maintained up to 6 months.

Regardless of the type of assistance provided, every effort was made to provide similar training conditions between treatment groups to approximate equivalent amounts of stepping practice. Nonetheless, small but significant differences were observed for training speed (0.01 m/s in therapist-assisted) and duration (18 seconds in robotic-assisted). Given the magnitudes of these differences, we believe the type of assistance provided during LT was the primary impetus for the 2-fold differences in gait speed improvements between treatment groups.

The small sample size and lack of blinded assessment are additional confounding factors. Despite these limitations, all efforts were made to standardize procedures and instructions during assessments. Further, observed differences between LT groups were consistent with published results. Separate laboratories have reported mean changes in walking speed of $\leq 0.07 \text{ m/s}$ in ambulatory subjects with neurological injury over 3 to 4 weeks of robotic-assisted LT.^{29,30} In contrast, previous data in stroke survivors^{6,9} indicate larger changes ($\geq 0.15 \text{ m/s}$) in SSV after 4 weeks of task-specific LT. The magnitudes of these changes are comparable to those observed in the present study.

Various factors may account for the differences observed between LT groups. One explanation may lie in the extent of aerobic stimulus elicited during therapist- and robotic-assisted LT. Previous data in subjects with incomplete SCI revealed

greater metabolic costs during therapist- versus robotic-assisted stepping, particularly when subjects were asked to simply "walk with the robot,"^{23,38} which was associated with different hip flexor electromyographic activity associated with swing initiation. When subjects were asked to exert maximal effort during robotic-assisted walking and were provided biofeedback, consistent with robotic-assisted LT provided in this study, differences in metabolic costs between stepping conditions were reduced, although other abnormal muscle activity patterns were observed.²³ Whether subjects maintained maximal effort during robotic-assisted stepping throughout the study is uncertain, although preliminary data indicate that metabolic activity during robotic-assisted stepping decreases over prolonged durations.^{38,39} Reduced metabolic activity during robotic-assisted LT may limit adaptations which occur during treadmill exercise in individuals poststroke, which are thought to be a primary factor contributing to improved ambulation.²⁴

The extent of guidance provided during robotic-assisted LT may be an additional factor that contributed to observed differences between treatment groups. Specifically, pelvis and trunk restraint coupled with passive swing assistance may have reduced volitional drive necessary for motor memory consolidation. While the alterations in muscle activity during swing phase assistance are described above, the use of pelvic and trunk restraint to provide postural support warrants further consideration. Before assessing metabolic costs of walking, Israel et al²³ revealed a larger metabolic cost of standing on the stationary treadmill belt without versus with the robotic device attached to the subjects. Although electromyographic activity of lower limb and trunk muscles were not collected, metabolic differences between conditions indicate indirectly that reduced muscle activity was necessary to maintain postural stability in the robotic device. Differences in volitional postural control may be magnified during therapist- versus robotic assisted LT. Further, and despite suggestions that supraspinal structures are activated similarly during passive and active tasks in subjects with stroke,⁴⁰ data from unimpaired subjects reemphasize the importance of volitional drive during task practice.⁴¹ Error reduction for postural and lower limb activity during robotic-assisted LT may limit subsequent unconstrained performance.²⁶ For example, provision of symmetrical gait patterns during robotic-assisted LT did not improve single limb stance time, although changes following therapist-assisted LT were substantial. These differences may be attributable to the inherently greater variability and provision of loosely constrained lower-limb trajectories²⁵ to enhance error detection⁴² during the course of therapist- versus robotic-assisted LT.²⁷

Importantly, reduced assistance can be provided by various robotic devices,⁴³ including the apparatus used in this study,²¹ but only in the sagittal plane for hip and knee trajectories. Whether reduced sagittal plane assistance at the limbs is sufficient to elicit large changes in locomotor function is unknown, particularly in light of the contribution of propulsive forces to gait speed and symmetry in hemiparetic subjects.^{32,44} Recent data in hemiparetic subjects during robotic-assisted stepping using different control algorithms which decrease limb assistance did not alter metabolic activity,⁴⁵ suggesting little expected difference with prolonged training. Moreover, whether sophisti-

cated devices are required to provide assistance during LT is still uncertain, however, as simple “mechanical” assistance at the limb has been shown to be equally effective as a manual facilitation technique to approximate normal gait kinematics poststroke.¹⁴

Changes in step length asymmetry in subjects with severe versus moderate gait impairments, and improved physical SF36 scores in those with severe impairment provided therapist-assisted LT are of additional interest, as few studies have observed such changes.⁴⁶ The potential range for improvement (ie, lack of ceiling effect) in more severely impaired subjects may account for differences in step length asymmetry. For changes in the physical SF36 scores, previous investigations have revealed similar improvements after exercise regimens,⁴⁷ which may explain why more severely impaired subjects who received an intense exercise regimen improved their perception of physical disability.

In summary, the present study indicates that, in chronic ambulatory stroke survivors, therapist-assisted LT is superior to robotic-assisted LT. Given the cost and continued development of rehabilitation devices, it is imperative to identify patients who may benefit from robotic-assisted training. Considering the present results, patients with chronic hemiparesis who can walk independently overground, even at very slow speeds, may be better served using therapist-assisted LT. As such, larger clinical trials assessing the effects of robotic-assisted LT utilizing this patient population may not be warranted. Rather, robotic LT may be indicated in nonambulatory, subacute stroke survivors, as suggested previously.^{13,20,21}

Sources of Funding

Research was funded by grant #H133B031127 and #H133G040065 from the National Institute of Disability and Rehabilitation Research, Department of Education.

Disclosures

None.

References

- Lord SE, Rochester L. Measurement of community ambulation after stroke: Current status and future developments. *Stroke*. 2005;36:1457–1461.
- Roth EJ, Merbitz C, Mroczek K, Dugan SA, Suh WW. Hemiplegic gait. Relationships between walking speed and other temporal parameters. *Am J Phys Med Rehabil*. 1997;76:128–133.
- Plummer P, Behrman AL, Duncan PW, Spiegel P, Saracino D, Martin J, Fox E, Thigpen M, Kautz SA. Effects of stroke severity and training duration on locomotor recovery after stroke: A pilot study. *Neurorehabil Neural Repair*. 2007;21:137–151.
- Barbeau H. Locomotor training in neurorehabilitation: Emerging rehabilitation concepts. *Neurorehabil Neural Repair*. 2003;17:3–11.
- Edgerton VR, Tillakaratne NJ, Bigbee AJ, de Leon RD, Roy RR. Plasticity of the spinal neural circuitry after injury. *Annu Rev Neurosci*. 2004;27:145–167.
- Ada L, Dean CM, Hall JM, Bampton J, Crompton S. A treadmill and overground walking program improves walking in persons residing in the community after stroke: A placebo-controlled, randomized trial. *Arch Phys Med Rehabil*. 2003;84:1486–1491.
- Macko RF, Ivey FM, Forrester LW, Hanley D, Sorkin JD, Katzel LI, Silver KH, Goldberg AP. Treadmill exercise rehabilitation improves ambulatory function and cardiovascular fitness in patients with chronic stroke: A randomized, controlled trial. *Stroke*. 2005;36:2206–2211.
- Pohl M, Mehrholz J, Ritschel C, Ruckriem S. Speed-dependent treadmill training in ambulatory hemiparetic stroke patients: A randomized controlled trial. *Stroke*. 2002;33:553–558.
- 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.
- 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;29:1122–1128.
- Barbeau H, Visintin M. Optimal outcomes obtained with body-weight support combined with treadmill training in stroke subjects. *Arch Phys Med Rehabil*. 2003;84:1458–1465.
- Kosak MC, Reding MJ. Comparison of partial body weight-supported treadmill gait training versus aggressive bracing assisted walking post stroke. *Neurorehabil Neural Repair*. 2000;14:13–19.
- Werner C, Bardeleben A, Mauritz KH, Kirker S, Hesse S. Treadmill training with partial body weight support and physiotherapy in stroke patients: A preliminary comparison. *Eur J Neurol*. 2002;9:639–644.
- Yagura H, Hatakenaka M, Miyai I. Does therapeutic facilitation add to locomotor outcome of body weight-supported treadmill training in nonambulatory patients with stroke? A randomized controlled trial. *Arch Phys Med Rehabil*. 2006;87:529–535.
- Lum P, Reinkensmeyer D, Mahoney R, Rymer WZ, Burgar C. Robotic devices for movement therapy after stroke: Current status and challenges to clinical acceptance. *Top Stroke Rehabil*. 2002;8:40–53.
- Wernig A, Muller S, Nanassy A, Cagol E. Laufband therapy based on ‘rules of spinal locomotion’ is effective in spinal cord injured persons. *Eur J Neurosci*. 1995;7:823–829.
- Behrman AL, Harkema SJ. Locomotor training after human spinal cord injury: A series of case studies. *Phys Ther*. 2000;80:688–700.
- 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.
- Werner C, Von Frankenberg S, Treig T, Konrad M, Hesse S. Treadmill training with partial body weight support and an electromechanical gait trainer for restoration of gait in subacute stroke patients: A randomized crossover study. *Stroke*. 2002;33:2895–2901.
- Mayr A, Kofler M, Quirbach E, Matzak H, Frohlich K, Saltuari L. Prospective, blinded, randomized crossover study of gait rehabilitation in stroke patients using the lokomat gait orthosis. *Neurorehabil Neural Repair*. 2007;21:307–314.
- Husemann B, Muller F, Krewer C, Heller S, Koenig E. Effects of locomotion training with assistance of a robot-driven gait orthosis in hemiparetic patients after stroke: A randomized controlled pilot study. *Stroke*. 2007;38:349–354.
- Hesse S, Werner C, Uhlenbrock D, von Frankenberg S, Bardeleben A, Brandl-Hesse B. An electromechanical gait trainer for restoration of gait in hemiparetic stroke patients: Preliminary results. *Neurorehabil Neural Repair*. 2001;15:39–50.
- Israel JF, Campbell DD, Kahn JH, Hornby TG. Metabolic costs and muscle activity patterns during robotic- and therapist-assisted treadmill walking in individuals with incomplete spinal cord injury. *Phys Ther*. 2006;86:1466–1478.
- Macko RF, Ivey FM, Forrester LW. Task-oriented aerobic exercise in chronic hemiparetic stroke: Training protocols and treatment effects. *Top Stroke Rehabil*. 2005;12:45–57.
- Schmidt RA, Lee TD. *Motor control and learning: A behavioral emphasis*. Champaign, IL: Human Kinetics Inc; 1999.
- Winstein CJ, Pohl PS, Lewthwaite R. Effects of physical guidance and knowledge of results on motor learning: Support for the guidance hypothesis. *Res Q Exerc Sport*. 1994;65:316–323.
- Cai LL, Fong AJ, Otoshi CK, Liang Y, Burdick JW, Roy RR, Edgerton VR. Implications of assist-as-needed robotic step training after a complete spinal cord injury on intrinsic strategies of motor learning. *J Neurosci*. 2006;26:10564–10568.
- Tombaugh TN. Test-retest reliable coefficients and 5-year change scores for the mmse and 3ms. *Arch Clin Neuropsychol*. 2005;20:485–503.
- Wirz M, Zemon DH, Rupp R, Scheel A, Colombo G, Dietz V, Hornby TG. Effectiveness of automated locomotor training in patients with chronic incomplete spinal cord injury: A multicenter trial. *Arch Phys Med Rehabil*. 2005;86:672–680.
- Peurala SH, Tarkka IM, Pitkanen K, Sivenius J. The effectiveness of body weight-supported gait training and floor walking in patients with chronic stroke. *Arch Phys Med Rehabil*. 2005;86:1557–1564.

31. Perry J. *Gait Analysis: Normal and Pathological Function*. Thorofare NJ: SLACK Inc; 1992.
32. Balasubramanian CK, Bowden MG, Neptune RR, Kautz SA. Relationship between step length asymmetry and walking performance in subjects with chronic hemiparesis. *Arch Phys Med Rehabil*. 2007;88:43–49.
33. Baer HR, Wolf SL. Modified emory functional ambulation profile: An outcome measure for the rehabilitation of poststroke gait dysfunction. *Stroke*. 2001;32:973–979.
34. Berg K, Wood-Dauphinee S, Williams JI. The balance scale: Reliability assessment with elderly residents and patients with an acute stroke. *Scand J Rehabil Med*. 1995;27:27–36.
35. Barak S, Duncan PW. Issues in selecting outcome measures to assess functional recovery after stroke. *NeuroRx*. 2006;3:505–524.
36. Kendall FP, McCreary EK, Provance PG. *Muscles: Testing and Function*. Baltimore, MD: Williams and Wilkins; 1993.
37. Bohannon RW, Smith MB. Interrater reliability of a modified ashworth scale of muscle spasticity. *Phys Ther*. 1987;67:206–207.
38. Israel JF, Hornby TG. Physiological responses of individuals with incomplete spinal cord injury during robotic-assisted treadmill walking. Combined Sections Meeting, American Physical Therapy Association. 2006:53.
39. 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.
40. Nelles G, Jentzen W, Jeuptner M, Muller S, Diener HC. Arm training induced brain plasticity in stroke studied with serial position emission tomography. *Neuroimage*. 2001;13:1146–1154.
41. Lotze M, Braun C, Birbaumer N, Anders S, Cohen LG. Motor learning elicited by voluntary drive. *Brain*. 2003;126:866–872.
42. Patton JL, Stoykov ME, Kovic M, Mussa-Ivaldi FA. Evaluation of robotic training forces that either enhance or reduce error in chronic hemiparetic stroke survivors. *Exp Brain Res*. 2006;168:368–383.
43. Reinkensmeyer DJ, Aoyagi D, Emken JL, Galvez JA, Ichinose W, Kerdanyan G, Maneeekobkunwong S, Minakata K, Nessler JA, Weber R, Roy RR, de Leon R, Bobrow JE, Harkema SJ, Edgerton VR. Tools for understanding and optimizing robotic gait training. *J Rehabil Res Dev*. 2006;43:657–670.
44. Bowden MG, Balasubramanian CK, Neptune RR, Kautz SA. Anterior-posterior ground reaction forces as a measure of paretic leg contribution in hemiparetic walking. *Stroke*. 2006;37:872–876.
45. Krewer C, Muller F, Husemann B, Heller S, Quintern J, Koenig E. The influence of different lokomat walking conditions on the energy expenditure of hemiparetic patients and healthy subjects. *Gait Posture*. 2007;26:372–377.
46. Silver KH, Macko RF, Forrester LW, Goldberg AP, Smith GV. Effects of aerobic treadmill training on gait velocity, cadence, and gait symmetry in chronic hemiparetic stroke: A preliminary report. *Neurorehabil Neural Repair*. 2000;14:65–71.
47. Mead GE, Greig CA, Cunningham I, Lewis SJ, Dinan S, Saunders DH, Fitzsimons C, Young A. Stroke: A randomized trial of exercise or relaxation. *J Am Geriatr Soc*. 2007;55:892–899.