Faster Is Better
Implications for Speed-Intensive Gait Training After Stroke

Anouk Lamontagne, PhD, PT; Joyce Fung, PhD, PT

***Background and Purpose*—**The instantaneous adaptations to speed and load changes during overground locomotion have major implications for mobility after stroke. We examined the extent to which stroke subjects could increase their overground walking speed with respect to speed and unloading changes.

***Methods*—**Twelve subjects with a unilateral stroke were evaluated while walking overground full weight bearing (FWB) or with body weight support (BWS) at preferred or fast speed. On the basis of their preferred walking speed, subjects were classified as high (≥45 cm/s) or low functioning (<45 cm/s). Gait speed, temporal distance factors (TDFs), as well as movements and muscle activation of the lower limbs were measured and compared across the conditions.

***Results*—**FWB-Fast condition induced marked (165%) increment in gait speed in all subjects. BWS at preferred speed induced faster speeds in low- but not the high-functioning subjects, whereas combined BWS and fast walking yielded further speed increments in the high-functioning subjects. Fast walking was associated with bilateral increases in joint excursion and muscle activation, as well as improved symmetry in some TDFs. BWS favored a hip flexion strategy in early swing while decreasing limb circumduction.

***Conclusions*—**This study shows that stroke subjects can increase substantially their walking speed without deleterious effects. Fast walking induces marked speed-related improvements in body and limb kinematics and muscle activation patterns. BWS during overground walking also increases gait speed, but to a lesser extent and only in low-functioning subjects. The combination of BWS with fast speed produces the greatest increments in walking speed in all subjects.
(*Stroke*. 2004;35:2543-2548.)

Key Words: exercise ■ hemiplegia ■ locomotion ■ rehabilitation

Walking after stroke is characterized by slow gait speed,[1] poor endurance,[2] and changes in the quality[3] and adaptability[4] of walking pattern. Among rehabilitation paradigms developed to improve mobility in stroke subjects, the most popular is treadmill training, alone[5,6] or combined with partial body weight support (BWS).[7–9] Such training paradigms, in which subjects are trained at their preferred speed, lead to improvements in gait speed that are modestly superior to those obtained by conventional gait training.[5,6] More recently, new training paradigms incorporating fast walking and intensive training regimens were proposed.[10–12] These paradigms, incorporating principles of sports training such as task-specificity, repetition, and training intensity, lead to dramatic improvements in walking speed.[12] However, little is known about the stroke subjects' capability of adapting to the demands of speed and load, depending on their initial functional performance.

The majority of training regimens involve treadmill walking (TW) with BWS. However, TW differs from overground locomotion in several aspects,[13,14] and the gains in walking speed achieved during treadmill training by hemiparetic subjects are not completely transferred to overground locomotion.[6,9,12] A new system developed in our laboratory allows subjects to walk overground while the lower extremities are partially unloaded.[15,16] In the present study, the instantaneous adaptations to fast walking and to BWS were examined during overground locomotion in a group of subjects with recent stroke. The purpose of this study was to investigate the extent to which stroke subjects can increase their speed and modify their gait pattern during (1) fast walking, (2) BWS, and (3) combined fast walking and BWS.

Methods

Subjects

Twelve subjects were recruited from the Jewish Rehabilitation Hospital with informed consent. Subjects (with characteristics listed in the Table) experienced a cerebrovascular accident <1 year previously in the territory of the middle (n=11) or posterior (n=1) cerebral artery, either of ischemic (n=10) or of hemorrhagic (n=2) origin. Inclusion criteria were: first time unilateral stroke; ability to walk 5 consecutive steps, either with or without assistance or walking aid; and gait speed slower than 75 cm/s. Exclusion criteria included brain stem or cerebellar lesion confirmed by computerized

Received August 4, 2004; accepted August 10, 2004.

From the Jewish Rehabilitation Hospital, Centre for Interdisciplinary Research in Rehabilitation; and the School of Physical and Occupational Therapy, McGill University, Montreal, Canada.

Correspondence to Dr Anouk Lamontagne, JRH Research Centre, 3205 Place Alton-Goldbloom, Laval (Quebec), Canada, H7V 1R2. E-mail anouk.lamontagne@mcgill.ca

***Stroke* is available at http://www.strokeaha.org** **DOI: 10.1161/01.STR.0000144685.88760.d7**

Subject Characteristics

Subject	Gender	Age (years)	Paretic Side	Time Since Stroke (days)	Gait Speed (cm/s)	Functional Level*
1	Male	88	Right	69	9	Low
2	Male	61	Left	46	13	Low
3	Male	70	Left	39	32	Low
4	Female	52	Left	47	34	Low
5	Male	54	Left	290	37	Low
6	Male	78	Left	31	42	Low
7	Male	76	Right	128	43	Low
8	Male	64	Right	55	45	High
9	Male	69	Right	47	45	High
10	Female	74	Left	36	53	High
11	Female	73	Left	39	63	High
12	Male	82	Right	41	73	High
Mean	—	70	—	72	41	—
SD	—	11	—	73	18	—

*Based on their gait speed, subjects were classified as low- (<45 cm/s) or high- (≥45 cm/s) functioning.

tomography and any pre-existing conditions that interfere with locomotion. A previous study by Perry et al[17] shows that walking speed of ≤0.4±0.18 m/s restricts a stroke individual's capacity for community ambulation. Thus, subjects were further classified (Table), on the basis of their preferred walking speed, as low (<45 cm/s) or high (≥45 cm/s) functioning. In the low-functioning group, 5 subjects had started to walk <1 week previously.

Experimental Design

The evaluation consisted of 4 walking conditions presented randomly: walking full weight bearing (FWB) at preferred (FWB-Pref) and maximal speed (FWB-Fast), and walking with BWS at preferred speed (BWS-Pref) and maximal speed (BWS-Fast). Two walking trials were assessed for each of the 4 conditions.

Walking Assessment

Subjects were evaluated on a 10-m walkway while walking in a body harness suspended overhead by a pressurized weight support system. This unique system provides constant BWS throughout the gait cycle while not preventing the center of mass (CoM) of the body to travel naturally up and down during the single- and double-limb support periods. Subjects were instructed to walk at preferred speed and as fast as possible with FWB or with BWS. To further encourage the subjects during the fast walking conditions, they were told to hurry as much as possible, as if they were trying to catch a bus, and reinforced with verbal encouragement and cheering throughout the walking trial. They were not discouraged from running if they could. Level of BWS was set at 30% of body weight for most subjects because such a level of unloading has been shown previously to yield positive results for hemiparetic subjects.[8,9,18] However, for 2 subjects of the low-functioning group, 50% of BWS was provided because this was preferred by the individual and allowed a better swing-through with the paretic limb. Subjects wore a harness at all times, and rest periods were given as needed. The walking speed or cadence during different loading conditions was not dictated by the use of a metronome or any artificial device. Instead, the different walking conditions were assessed as they would be presented to the patient in the clinical setting, and speed was our primary outcome of interest.

A Vicon 512 6-camera motion analysis system (Oxford Metrics) was used to acquire body movements at 120 Hz. A 9-segment model was reconstructed on the basis of a 23-marker set (PlugInGait; Vicon) comprising the lower body segments, pelvis, trunk, and head. Electromyographic (EMG) from paretic and nonparetic lower limb muscles (medial gastrocnemius [MG], tibialis anterior [TA], semitendinosus [ST], and rectus femoris [RF]) was recorded at 1080 Hz using an 8-channel EMG system (TelEMG; BTS). After preamplification and band-pass filtering (10 to 400 Hz), EMG signals were rectified and smoothed at 20 Hz, whereas kinematic data were low-pass filtered at 8 Hz for offline analysis.

Data Analysis

The primary outcome measure of this study was gait speed. Secondary outcome measures included temporal distance factors (TDFs), sagittal plane segmental angular excursions, CoM, and toe trajectory along the mediolateral (ML) axis, as well as EMG amplitude. TDFs retained for analysis were step length and cycle duration, as well as the percentage of time spent in stance, single, and double support periods. Foot strikes and foot-off events were determined using toe and heel marker displacements along the anteroposterior (AP) axis. All data were normalized to 100% of the gait cycle duration. Walking speed was calculated as the average velocity of the body CoM along the direction of walking for each gait cycle. EMG integrals were computed for functionally relevant time windows of the gait cycle (%): MG activation at push-off [30%:70%], TA

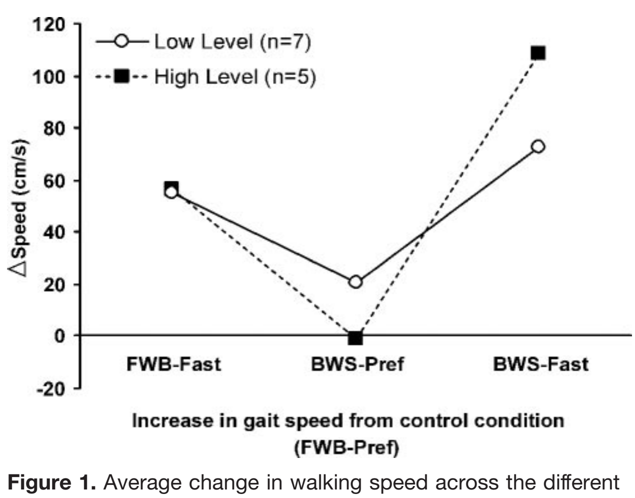

Figure 1. Average change in walking speed across the different conditions with reference to the preferred speed condition at FWB. The walking conditions illustrated are: FWB-Fast, BWS-Pref, and BWS-Fast.

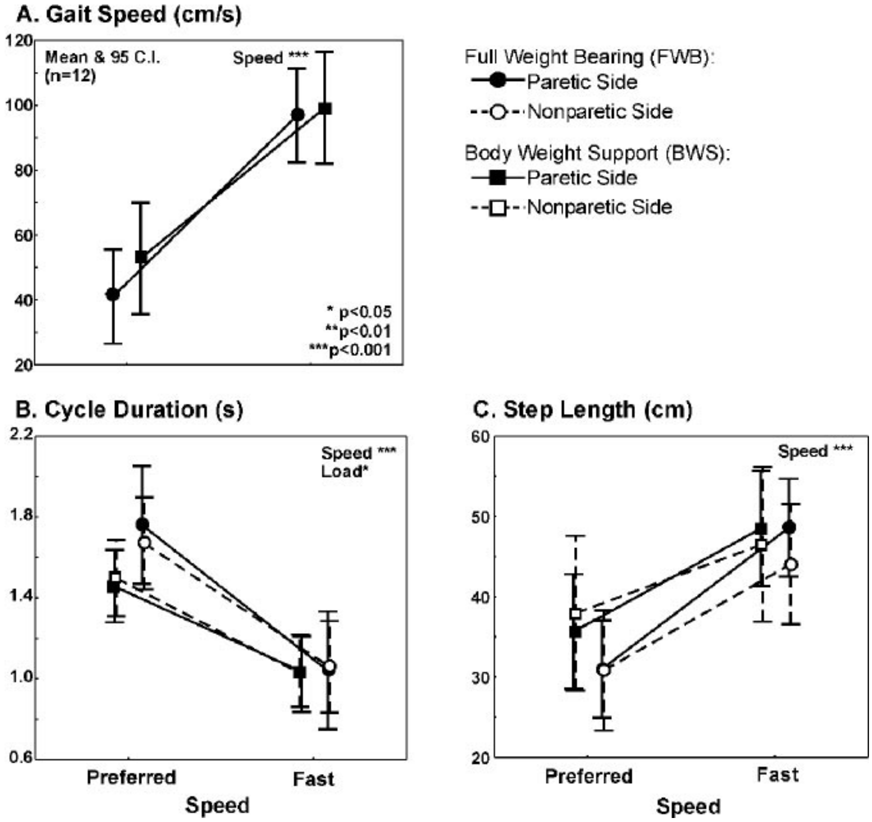

Figure 2. Average walking speed of the stroke subjects (A) and respective values of cycle duration (B) and step length (C) for the paretic and nonparetic limbs while walking FWB or with BWS at preferred or fast speed. Values illustrated represent the mean ±95% CI. For all figures, only significant main and interaction effects of load (full weight vs BWS), speed (preferred vs fast), or side (paretic vs nonparetic) are indicated on each graph.

activation at toe-off [60%:80%], ST activation in early stance [0%:30%], and RF hip flexion burst at toe-off [60%:80%]. All outcome measures were first calculated separately for every gait cycle (n=8 to 12 cycles) and later averaged for every subject. The first and last 2 gait cycles of each walking trial were always excluded from the analysis to avoid acceleration and deceleration phases. Two subjects ran for a few steps in one of the FWB-fast condition trials, but those gait cycles were not included in the analysis.

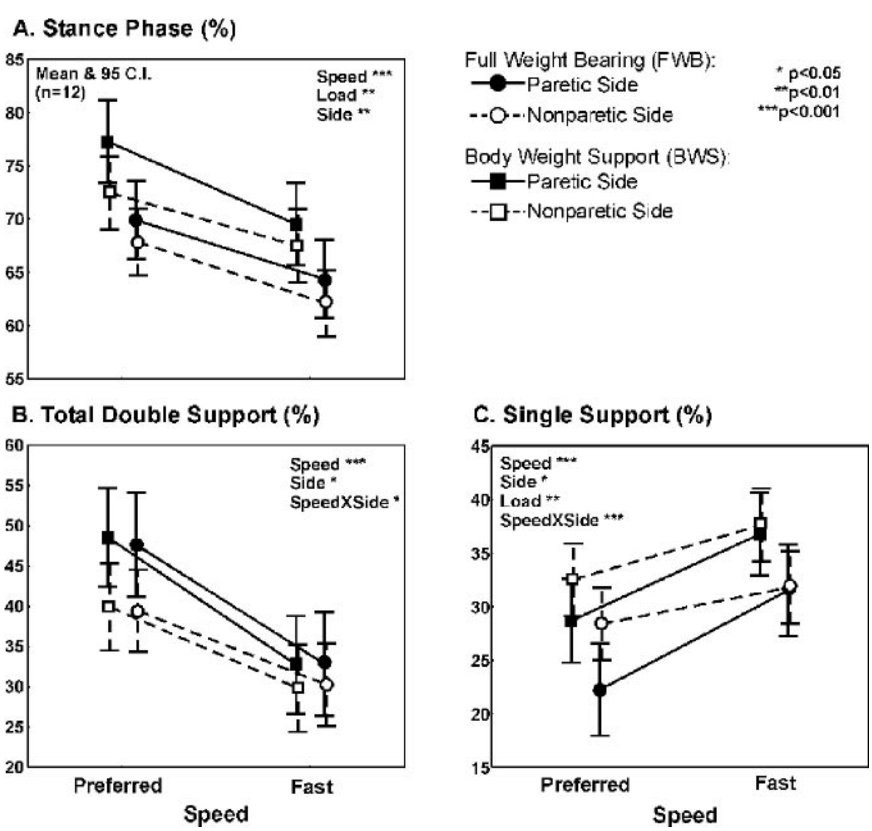

Figure 3. Percentage of time spent in the stance phase, as well as the percentage of time spent in total double-support (B) and single-support (C) subphases on the paretic and nonparetic sides while walking FWB or with BWS at preferred or fast speed. Values illustrated represent the mean ±95% CI.

Statistical Analysis

The effect of load (FWB versus BWS) and speed (Pref versus Fast) on gait speed was analyzed using a 2-way ANOVA. The effects of load, speed, and limb (paretic versus nonparetic) on all other kinematic, TDF, and EMG variables were determined by using 3-way ANOVAs (Statistica 6.0). A *P* value of 0.05 was accepted as significant after Bonferroni adjustments. When significant main or interaction effects were present, post hoc comparisons were made by Tukey tests.

Results

The average change in gait speed attributable to fast walking without BWS was much greater in the low-functioning subjects (210%) compared with the high-functioning group (103%), although similar absolute speed increments were displayed in both groups ($\delta_{Low\ Level}$=55 cm/s versus $\delta_{High\ Level}$=56 cm/s; Figure 1). BWS alone induced faster speeds in the low-functioning (δ=21 cm/s or 69%) but not the high-functioning (δ=−1 cm/s or −2%) group. The combination of BWS and fast walking induced greatest increments in gait speed, revealing an interaction effect attributable to speed and BWS ($\delta_{Low\ Level}$=72 cm/s, 258% versus $\delta_{High\ Level}$=108 cm/s, 95%; Figure 1), depending on the functional level.

Increase in gait speed in the fast walking conditions was accompanied by shorter cycle durations and larger step lengths, regardless of BWS (Figure 2). Figure 3 shows that fast walking induces a lesser proportion of stance duration, along with shorter double-support and longer single-support durations. Fast walking improved symmetry in double- and single-support proportions between the paretic and nonparetic sides, whereas BWS reduced stance proportion without significant improvements in symmetry.

When walking at faster speeds, subjects displayed bilateral and symmetrical increases in hip and knee excursions. The latter was explained by greater knee flexion at weight acceptance and during swing, whereas larger hip excursions were associated with increased extension in late stance and flexion in late swing (*P*=0.001 to 0.04). Walking with BWS-Pref or BWS-Fast induced larger hip excursions on the paretic and nonparetic sides because of larger (*P*<0.01) late-stance hip extension and swing-phase hip flexion. Fast walking or BWS did not improve symmetry of the lower limb movements. The occurrence of undesirable movement patterns such as increased limb circumduction or large side-to-side displacement of body CoM was also examined. Fast walking slightly increased the ML deviation of the paretic and nonparetic foot trajectories, whereas BWS had the opposite effect of slightly decreasing the ML deviation (Figure 4). Side-to-side movements of the body CoM were reduced at faster walking speeds (*P*<0.001; data not shown), whereas BWS did not induce any significant effects (*P*>0.05).

Fast walking required larger muscle activation in all recorded muscles (Figure 5) on the paretic and nonparetic sides. BWS did not induce any changes, except for RF, for which activation increased at faster speed, especially on the paretic side.

Discussion

Faster Is Better

Stroke subjects can increase their overground walking speed 2 to 3 times beyond comfortable levels given proper instructions and a safe environment. Such increase is attributable to larger step lengths and shorter cycle durations on the paretic and nonparetic sides, regardless of the functioning level. Muscle strength, more specifically, ankle push-off during the stance phase and hip flexion pull-off in early swing,[19,20] are known to be major determinants of walking speed after stroke. Slow walking after stroke may be a behavioral adaptation to poor endurance, poor balance, and the individual's perceived limits of stability. Use of a safety harness may have unmasked the latent locomotor behavior and its capability to be driven fast. Other common factors after stroke, such as altered perception of self-motion,[21] and cognitive or attention deficits,[22] may also play a role.

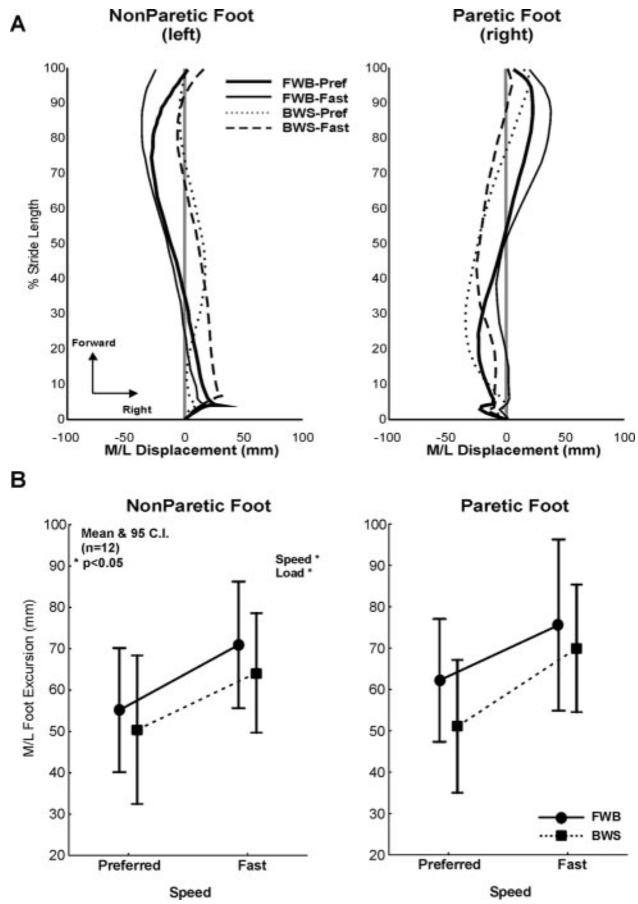

Figure 4. The top traces (A) represent one example of the ML displacement of the foot (*x* axis) as a function of stride length (*y* axis) for the paretic (left) and nonparetic (right) limbs across the different walking conditions: FWB-Pref, FWB-Fast, BWS-Pref, and BWS-Fast. Bottom graphs (B) represent the mean (±95% CI) ML excursion of the foot displacements during the same walking conditions.

Fast walking improves the kinematics and muscle activation patterns of hemiparetic gait, which are consistent with the speed-dependent changes reported in healthy subjects.[23] In contrast to fast TW,[24] symmetry of some TDFs also improved with overground fast walking, suggesting that different strategies may be used in adapting to different modes of locomotion (treadmill versus overground). Although these improvements provide a strong rationale for training, the question of fatigability, energy cost, and pres-

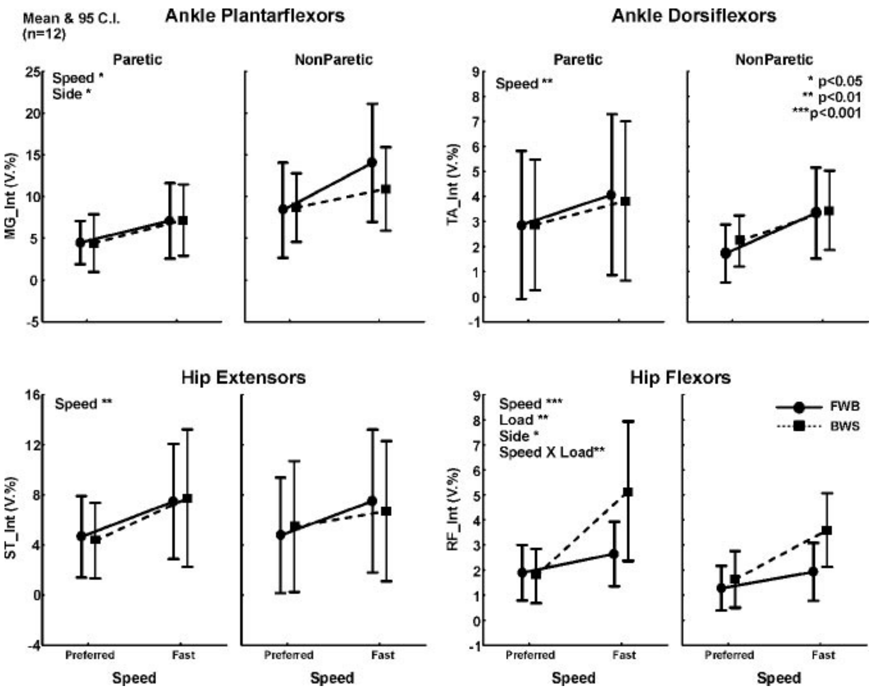

Figure 5. Activation amplitude of the MG, TA, ST, and RF on the paretic and nonparetic side while walking FWB or with BWS at preferred or fast speed. Titles of each graph indicate the interpreted muscle function on the basis of the time window during which activation amplitude was measured during the gait cycle. Mean values and respective 95% CIs are illustrated.

ence of comorbidities may be raised. Paretic gait is known to be associated with a high-energy demand compared with normal gait,[25] and stroke subjects show poor endurance.[2] However, despite higher heart rates and larger muscle activation levels at faster speeds, stroke subjects' overall energy and cardiac costs correlate negatively with gait speed,[24] suggesting greater efficiency at faster walking speeds. In fact, when walking faster, stroke subjects approach the bandwidth [1.2 to 1.8 m/s] of walking speed at which optimal upper body segment coordination[26] and energy consumption[27] are observed. This greater efficiency may be attributable to more appropriate timing of lower limb muscles,[24] improved movement coordination, and possibly facilitation of intralimb and interlimb energy transfers. Despite these advantages of fast walking, its use may not be recommended for patients with comorbidities such as heart disease or exercise-exacerbated muscle/joint pain, unless close monitoring of vital signs, exertion, or pain level allows for safe and comfortable use.

BWS Is Beneficial to Low-Functioning Subjects

In the present study, only subjects walking at an initial speed $<$45 cm/s increased their comfortable speed when walking with BWS. High-functioning subjects did not increase their comfortable speed with BWS but did so when walking at maximal pace. These results suggest that BWS may be preferentially beneficial to low-functioning subjects, whereas high-functioning subjects may benefit from the combined use of BWS and fast walking. As observed in supported TW,[18] BWS did not significantly improve symmetry in TDFs. However, in contrast to what was reported for healthy[28] and stroke subjects[18] during supported treadmill ambulation, no reduction in antigravitary muscle activation was observed in the present study. The lower demand on antigravitary muscles induced by the unloading of the lower limbs may be counteracted by a higher demand because of the increase in walking speed, which outlines a possible advantage of overground BWS training over weight-supported TW. The increase in RF activation at toe-off, especially on the paretic side, suggests the use of a hip flexor strategy. This strategy, along with the reduced limb circumduction observed with BWS, is consistent with the patients' self-report of increased ease in limb swing with BWS. This improvement may be explained by the more upright position of the trunk with BWS,[29] which facilitates terminal stance hip extension and, in return, recruitment of the hip flexors in early swing. Apart from facilitating stepping, BWS during overground walking also increases the relative loading of the paretic limb and assists balance.[29] These effects on stepping, weight bearing, and balance, combined with the speed increments experienced by low-functioning stroke subjects in the present study, suggest overground BWS to be useful for locomotor training early after stroke and for more severely disabled subjects. When longer walking distances or specific speed levels are targeted, as for aerobic training, BWS can be combined with TW.

Conclusion

Fast walking induces speed-dependent adaptations that improve the overall walking pattern of stroke subjects, with no observable deleterious effects. On the basis of task specificity, speed-intensive training should reinforce improved walking behavior, while enhancing cardiovascular fitness, muscle power, motor coordination, and postural control to cope with the increase in walking speed. BWS during overground locomotion is preferentially beneficial to low-functioning subjects, inducing an instantaneous increase in gait speed while favoring a hip flexor strategy. In contrast with the conclusions drawn from a recent review on supported treadmill ambulation,[30] use of BWS during overground locomotion should be recommended as a useful intervention strategy

in early rehabilitation with severely disabled subjects, as evidenced by its instantaneous improvement on gait speed, stepping, weight bearing, and balance.

Acknowledgments

A.L. was the recipient of a postdoctoral fellowship from the Canadian Institutes of Health Research (CIHR). We are grateful to Rukshana Gheyara, Laura Galiana, and Roain Bayat for their assistance, and to the Jewish Rehabilitation Hospital (JRH) Foundation and CIHR for their financial support.

References

1. von Schroeder HP, Coutts RD, Lyden PD, Billings E Jr, Nickel VL. Gait parameters following stroke: a practical assessment. *J Rehabil Res Dev*. 1995;32:25–31.
2. Dean CM, Richards CL, Malouin F. Walking speed over 10 metres overestimates locomotor capacity after stroke. *Clin Rehabil*. 2001;15: 415–421.
3. Olney SJ, Richards CL. Hemiparetic gait following stroke. Part I: characteristics. *Gait Posture*. 1996;4:136–148.
4. Said CM, Goldie PA, Patla AE, Sparrow WA, Martin KE. Obstacle crossing in subjects with stroke. *Arch Phys Med Rehabil*. 1999;80: 1054–1059.
5. Richards CL, Malouin F, Wood-Dauphinee S, Williams JI, Bouchard JP, Brunet D. Task-specific physical therapy for optimization of gait recovery in acute stroke patients. *Arch Phys Med Rehabil*. 1993;74:612–620.
6. Laufer Y, Dickstein R, Chefez Y, Marcovitz E. The effect of treadmill training on the ambulation of stroke survivors in the early stages of rehabilitation: a randomized study. *J Rehabil Res Dev*. 2001;38:69–78.
7. Hesse S, Bertelt C, Jahnke MT, Schaffrin A, Baake P, Malezic M, Mauritz KH. Treadmill training with partial body weight support compared with physiotherapy in nonambulatory hemiparetic patients. *Stroke*. 1995;26:976–981.
8. da Cunha IT Jr, Lim PA, Qureshy H, Henson H, Monga T, Protas EJ. Gait outcomes after acute stroke rehabilitation with supported treadmill ambulation training: a randomized controlled pilot study. *Arch Phys Med Rehabil*. 2002;83:1258–1265.
9. 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.
10. Dean CM, Richards CL, Malouin F. Task-related circuit training improves performance of locomotor tasks in chronic stroke: a randomized, controlled pilot trial. *Arch Phys Med Rehabil*. 2000;81: 409–417.
11. 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.
12. 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.
13. Murray MP, Spurr GB, Sepic SB, Gardner GM, Mollinger LA. Treadmill vs floor walking: kinematics, electromyogram, and heart rate. *J Appl Physiol*. 1985;59:87–91.
14. Pearce ME, Cunningham DA, Donner AP, Rechnitzer PA, Fullerton GM, Howard JH. Energy cost of treadmill and floor walking at self-selected paces. *Eur J Appl Physiol Occup Physiol*. 1983;52:115–119.
15. Barbeau H, Lamontagne A, Ladouceur M, Mercier I, Fung J. Optimizing locomotor function with body weight support training and functional electrical stimulation. In Latash ML, Levin MF, eds. *Progress in Motor Control: Effects of Age, Disorders, and Rehabilitation*, vol 3. Windsor, Canada: Human Kinetics;2003:237–251.
16. Fung J, Barbeau H, Roopchand S. Partial weight support improves force generation and postural alignment during overground locomotion following stroke. *Soc Neurosci Abstr*. 1999;25:907.
17. Perry J, Garrett M, Gronley JK, Mulroy SJ. Classification of walking handicap in the stroke population. *Stroke*. 1995;26:982–989.
18. Hesse S, Helm B, Krajnik J, Gregoric M, Mauritz KH. Treadmill training with partial body weight support: influence of body weight release on the gait of hemiparetic patients. *J Neurol Rehabil*. 1997;11:15–20.
19. Nadeau S, Gravel D, Arsenault AB, Bourbonnais D. Plantarflexor weakness as a limiting factor of gait speed in stroke subjects and the compensating role of hip flexors. *Clin Biomech (Bristol, Avon)*. 1999;14: 125–135.
20. Olney SJ, Griffin MP, McBride ID. Temporal, kinematic, and kinetic variables related to gait speed in subjects with hemiplegia: a regression approach. *Phys Ther*. 1994;74:872–885.
21. Vaina LM, Cowey A, Eskew RT Jr, LeMay M, Kemper T. Regional cerebral correlates of global motion perception: evidence from unilateral cerebral brain damage. *Brain*. 2001;124:310–321.
22. Marshall SC, Grinnell D, Heisel B, Newall A, Hunt L. Attentional deficits in stroke patients: a visual dual task experiment. *Arch Phys Med Rehabil*. 1997;78:7–12.
23. Murray MP, Mollinger LA, Gardner GM, Sepic SB. Kinematic and EMG patterns during slow, free, and fast walking. *J Orthop Res*. 1984;2: 272–280.
24. Hesse S, Werner C, Paul T, Bardeleben A, Chaler J. Influence of walking speed on lower limb muscle activity and energy consumption during treadmill walking of hemiparetic patients. *Arch Phys Med Rehabil*. 2001; 82:1547–1550.
25. Corcoran PJ, Brengelmann GL. Oxygen uptake in normal and handicapped subjects, in relation to speed of walking beside velocity-controlled cart. *Arch Phys Med Rehabil*. 1970;51:78–87.
26. Wagenaar RC, Beek WJ. Hemiplegic gait: a kinematic analysis using walking speed as a basis. *J Biomech*. 1992;25:1007–1015.
27. Cavagna GA, Willems PA, Heglund NC. The role of gravity in human walking: pendular energy exchange, external work and optimal speed. *J Physiol*. 2000;528:657–668.
28. Ivanenko YP, Grasso R, Macellari V, Lacquaniti F. Control of foot trajectory in human locomotion: role of ground contact forces in simulated reduced gravity. *J Neurophysiol*. 2002;87:3070–3089.
29. Roopchand S, Fung J, Barbeau H. Locomotor training and the effects of unloading on overground locomotion following stroke. In Columbus F, ed. *Progress in Stroke Research*. New York, NY: Nova Science. In press.
30. Moseley AM, Stark A, Cameron ID, Pollock A. Treadmill training and body weight support for walking after stroke. *Cochrane Database Syst Rev*. 2003:CD002840.