

Gait Training Combining Partial Body-Weight Support, a Treadmill, and Functional Electrical Stimulation: Effects on Poststroke Gait

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Background and Purpose

Treadmill training with harness support is a promising, task-oriented approach to restoring locomotor function in people with poststroke hemiparesis. Although the combined use of functional electrical stimulation (FES) and treadmill training with body-weight support (BWS) has been studied before, this combined intervention was compared with the Bobath approach as opposed to BWS alone. The purpose of this study was to evaluate the effects of the combined use of FES and treadmill training with BWS on walking functions and voluntary limb control in people with chronic hemiparesis.

Subjects

Eight people who were ambulatory after chronic stroke were evaluated.

Methods

An A₁-B-A₂ single-case study design was applied. Phases A₁ and A₂ included 3 weeks of gait training on a treadmill with BWS, and phase B included 3 weeks of treadmill training plus FES applied to the peroneal nerve. The Stroke Rehabilitation Assessment of Movement was used to assess motor recovery, and a videography analysis was used to assess gait parameters.

Results

An improvement (from 54.9% to 71.0%) in motor function was found during phase B. The spatial and temporal variables cycle duration, stance duration, and cadence as well as cycle length symmetry showed improvements when phase B was compared with phases A₁ and A₂.

Discussion and Conclusions

The combined use of FES and treadmill training with BWS led to an improvement in motor recovery and seemed to improve the gait pattern of subjects with hemiparesis, indicating the utility of this combination method during gait rehabilitation. In addition, this single-case series showed that this alternative method of gait training—treadmill training with BWS and FES—may decrease the number of people required to carry out the training.



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Gait restoration is a major goal in poststroke neurological rehabilitation. For this reason, the recovery of independent walking is important in rehabilitation studies. Gait training on a treadmill with body-weight support (BWS) has received special attention. It consists of a suspension system to which a patient is connected so that weight shifting, balance, and stepping can be controlled; walking is facilitated by a treadmill.¹ Several studies¹⁻³ with promising outcomes have shown the feasibility of supported treadmill ambulation training in patients with stroke, but whether it is superior to other gait therapies is still under dispute.⁴ According to Visintin and Barbeau,² partial unloading of the lower extremities (40%) in subjects with hemiparesis results in a straighter trunk and knee alignment during the loading phase, a decrease in double-limb support time, and an increase in single-limb support time, stride length, and speed. On the basis of research with quadrupeds, indirect evidence suggests that this rehabilitation strategy apparently drives spinal motor programs through proprioceptive inputs and modulates spinal rhythm generators.^{5,6} Furthermore, it may lead to an improvement in sensory inputs and better functional motor reorganization.^{7,8}

According to the specificity of learning hypothesis,⁹ optimal motor learning occurs when performance during practice is well matched to that required for retention or transference conditions. According to Schmidt and Lee,¹⁰ motor learning reflects a neural specificity of practice because it involves the integration of motor information and sensory information available during practice. The specificity of learning hypothesis is consistent with advances in neurorecovery and neuroplasticity, which have shown that task-specific activity results in

changes in the nervous system that correlate with improvements in motor behavior. Animal and human work in locomotor recovery is particularly relevant to the neurophysiological rationale for step training on a treadmill, given that it specifically addresses how neuroplasticity is induced by repetitive locomotor activity that attempts to optimize the sensorimotor experience of walking at the spinal and supraspinal levels.¹¹⁻¹³

People with hemiparesis often display abnormal gait patterns, such as equinovarus (excessive plantar flexion and inversion) or foot drop (excessive plantar flexion), in which selective control impairments are particularly prominent in the feet. During walking, a person's big toe and outer foot margin rub against the ground, thus putting the person at risk of sustaining sprains and other ankle injuries.¹⁴ To minimize these patterns, electrical stimulation to correct spastic foot drop in hemiplegia was first applied by Liberson and coworkers in 1961.¹⁵ Surface electrodes were applied to the peroneal nerve at the fibular head, and a stimulator worn around the waist was controlled by a switch in the heel of the shoe worn on the affected limb. When a subject raised the heel to take a step, the stimulator was activated. Stimulation stopped when the heel came in contact with the ground again. This system, known as the peroneal stimulator, produces foot dorsiflexion and eversion during the swing phase of gait. Other studies^{16,17} have shown that peroneal stimulation to prevent foot drop in people with stroke improves walking, because it can provide critical practice of close-to-normal movements by electrically inducing muscle contraction and coordinated movements not volitionally possible.

Functional electrical stimulation (FES), based on the concepts described by Liberson et al,¹⁵ uses elec-

trical signals to activate peripheral nerves and control functional movements. This technique makes use of afferent feedback during contraction, a process that, with a patient's help, may maximize motor relearning during active repetitive movement training.^{18,19}

The combined use of FES and partial BWS training was previously reported.²⁰⁻²³ Hesse et al²⁰ investigated the use of multichannel electrical stimulation combined with treadmill training and partial BWS for subjects with hemiplegia. After the training program, improvements were seen in gait parameters such as speed, stride length, and cadence. That study had important implications for walking in subjects with hemiplegia and showed that the combined use of FES and partial BWS training improved their gait pattern. However, that study was carried out with subjects in both chronic and acute poststroke phases, when spontaneous functional recovery is to be expected.²⁴ In addition, FES was applied to the peroneal nerve and to the quadriceps femoris, biceps femoris, and pelvic stabilization muscles, according to the needs of each individual. The combined intervention with FES and partial BWS training was compared with conventional physical therapy (Bobath approach) as opposed to partial BWS training alone.

In a study of the combined use of FES and partial BWS training, Daly and Ruff²² used intramuscular electrodes to stimulate lower-limb muscles, but no comparisons were made between combined therapies and one training method alone. We found no published studies comparing the influence of a combination of FES and partial BWS training with the influence of partial BWS training alone on the gait pattern of subjects with chronic hemiparetic stroke.

Effects of Gait Training on Poststroke Gait

The aims of this study were: (1) to compare the effects of the combined use of FES and partial BWS training with the effects of partial BWS training alone on walking functions and voluntary limb control and (2) to investigate whether the use of FES in conjunction with partial BWS training provided any additional benefit to subjects with chronic hemiparesis. We hypothesized that the combined use of FES and partial BWS training would provide greater improvement in gait outcomes than partial BWS training alone. The gait outcomes analyzed were motor function and gait parameters (stride length, cycle duration, gait speed, stance duration, swing duration, cadence, cycle length symmetry, swing duration symmetry, and stance duration symmetry).

Method

Subjects

Eight people who were ambulatory after chronic stroke (2 women and 6 men, age $[\bar{X} \pm SD] = 56.6 \pm 10.26$ years, stroke interval $= 17.3 \pm 10.9$ months) took part in the study. Two subjects had right-side hemiparesis, and 6 subjects had left-side hemiparesis, which was caused by right or left supratentorial ischemic stroke ($n=6$) or intracerebral hemorrhage ($n=2$). All participants signed an informed consent form.

Spasticity (hypertonicity) was examined with the Modified Ashworth Spasticity Scale for lower-limb muscles. Levels ranged from 0 to 5, where 0 represents no increase at all in muscle tone (velocity-dependent resistance to stretch) and 5 indicates that the joint was rigid in flexion or extension.²⁵ Over-ground walking was assessed with the Functional Ambulation Category test,²⁶ which is based on a walking distance of 10 m. The test includes 6 levels of personnel support needed for gait. Level 0 describes people unable to walk or requiring the help of 2 or more people.

At level 1, people need the continuous support of 1 person to help them carry their weight and maintain their balance. At level 2, people are dependent on the continuous or intermittent support of 1 person to help with balance or coordination. At level 3, people need only verbal supervision. At level 4, help is required on stairs and uneven surfaces. Level 5 describes people who can walk independently in any given place.

The following inclusion criteria were considered in the selection of the subjects: an interval of greater than 6 months after stroke; spasticity classified at level 2 or 3 according to the Modified Ashworth Spasticity Scale (because this should allow people to walk with or without the help of a cane or another person); over-ground walking classified at level 2 or 3 according to the Functional Ambulation Category; no clinical signs of heart failure (New York Heart Association grade 0),²⁷ arrhythmia, or angina pectoris; no other orthopedic or neurological diseases impairing gait; and no severe cognitive or communication impairments.

Motor Function

Motor recovery was assessed before and 1 day after each treatment period with the Stroke Rehabilitation Assessment of Movement (STREAM), which is an instrument for monitoring basic mobility and voluntary movement of the limbs.²⁸ The STREAM is a 25-item scale that uses 4 points for some items and 2 points for others. The maximum score is 60; higher scores indicate better function. According to Ahmed et al,²⁹ STREAM shows good measurement properties. In that study, the STREAM was compared with the Berg Balance Scale, the Barthel Index, and the Timed "Up & Go" Test. The results showed that the STREAM was as accurate as the other scales in predicting gait speed and functional

poststroke ability. Two independent physical therapists assessed outcome measurements; the intraclass correlation coefficient for interrater reliability for the STREAM was .93.

Gait Analysis

The over-ground walking variables were measured as the subjects walked along a 6-m walkway. Acceleration and deceleration components were not included in the data. The subjects were assessed before and 1 day after each treatment period. Four subjects used a single-point cane during each assessment. The subjects walked at their self-selected speed along the walkway 3 times, and the 3 trials were recorded as definitive data for the gait parameters. These values were used to compute the following parameters: stride length (in meters), cycle duration (in seconds), gait speed (in meters per second), stance duration (in seconds), swing duration (in seconds), cadence (in steps per minute), cycle length symmetry, swing duration symmetry, and stance duration symmetry.

The gait analysis system included 5 digital video cameras (JVC Professional Dv Camcorder Gy-DV300*) placed to provide lateral, anterior, and posterior views of the subjects. Camera calibration was based on a direct linear transformation method, and the calibration parameters were used for a 3-dimensional reconstruction of the markers. Before the subjects walked along the walkway, retroreflective spherical markers (diameter = 10 mm) were attached to the big toe and heel of each foot. The kinematic analysis uncertainty related to the spatial measurements (eg, stride length) was ± 0.002 m. Given the frame rate used, the uncertainty related to the temporal measurements was ± 0.0167 second.

* JVC Company of America, 1700 Valley Rd, Wayne, NJ 07470.

Table 1.Gait Ability of Each Subject^a

Subject No.	MA				BWS (%)				Speed (m/s)				FES Time (min)			
	PT	A ₁	B	A ₂	PT	A ₁	B	A ₂	PT	A ₁	B	A ₂	PT	A ₁	B	A ₂
1	Yes	Yes	No	No	30	25	25	25	0.2	0.6	1	1	20	35	45	45
2	Yes	No	No	No	30	25	25	25	0.2	0.4	0.8	0.8	30	45	45	45
3	No	No	No	No	30	16	0	0	0.6	1.1	2	2	35	45	45	45
4	No	No	No	No	30	25	15	15	0.6	1	1.4	1.4	35	45	45	45
5	No	No	No	No	30	30	20	20	0.3	1	1.1	1.1	30	40	45	45
6	Yes	Yes	No	No	30	30	25	25	0.6	1.1	1.5	1.5	35	40	45	45
7	No	No	No	No	30	20	0	0	0.6	1.3	1.5	1.5	35	40	45	45
8	Yes	Yes	Yes	Yes	30	30	30	30	0.3	0.3	0.3	0.3	20	35	45	45

^a A₁=data obtained after phase A₁, A₂=data obtained after phase A₂, B=data obtained after phase B, BWS=body-weight support, FES=functional electrical stimulation, MA=manual assistance, PT=pretraining data, speed=gait speed at which the subjects were trained.

(1/60 second). Both variability measurements were about 10 times smaller than the intrasubject and intersubject variabilities observed in the experiments. The camera system collected gait parameters at 60 Hz with a shutter speed of 1/500 second. A Dvideow System³⁰ was used to process the kinematic parameters.

Training Protocol

A treadmill system similar to that described previously was used in this study.³¹ Harness-secured participants walked on a treadmill that was connected to an overhead suspension system positioned over the treadmill (Athletic Speedy 3[†]). The suspension system was an overhead-motorized pneumatic lift with a digital readout displaying the amount of BWS (Challenger 2 MSI-3360[‡]).

Training started with 30% BWS; the BWS was decreased progressively as the subjects increased their activity tolerance and were able to carry the remaining load on the paretic leg throughout stance and swing without the help of a physical therapist.

Two trainers were involved in the therapy of all of the subjects. During each session, the therapists decided, on the basis of clinical assessment, when to decrease the BWS for each subject. After 6 sessions, 7 subjects showed reduced BWS (from 30% to 25%); at the end of the study, they needed about 17% BWS (Tab. 1). Only 1 subject still needed 30% BWS at the end of the training period (Tab. 1). The subjects were weighed weekly to determine BWS reloading.

During each training session, the treadmill speed was increased according to the ability of the subjects, who were instructed to walk at a comfortable speed and encouraged to walk as fast as possible while maintaining a good gait pattern. In other words, they needed to be able to maintain proper trunk and limb alignment and transfer weight onto the hemiplegic limb. Treadmill speed was adjusted to a comfortable cadence and stride length for each subject. The mean treadmill speed was 0.4 m/s (range=0.2–0.6 m/s) at the beginning of gait training (Tab. 1). At the beginning of each training session, the subjects walked at the same speed at which they had stopped in the previous session. This

speed was increased according to the gait quality of each subject. When speed was increased and a subject failed to maintain trunk and limb alignment or was unable to perform initial contact properly, speed was reduced once again. After 9 sessions, a mean treadmill speed of 0.9 m/s (range=0.3–1.0 m/s) was reached; speed reached 1.2 m/s (range=0.3–1.5 m/s) at the completion of session 27 (Tab. 1).

Subjects could hold onto the horizontal bars attached to the sides of the treadmill for stability. Manual assistance, such as paretic limb loading, knee control, help in hip and trunk erection, and body weight shifting, was given according to individual needs. All subjects received verbal cueing during the training. Instructions about trunk alignment, step length, and knee flexion during the swing phase also were given according to individual requirements.

Functional electrical stimulation time (in minutes) was adjusted according to verbal feedback from the subjects during the 20- to 45-minute stimulation period (Tab. 1). The subjects were instructed to say when they felt fatigue related to dorsiflex-

[†] Athletic Indústria e Comércio, Rua Barão de Tefé 326, Joinville, Santa Catarina, Brazil CEP 89223-350.

[‡] Data Weighing Systems, Inc, 2100 Landmeier Rd, Elk Grove, IL 60007.

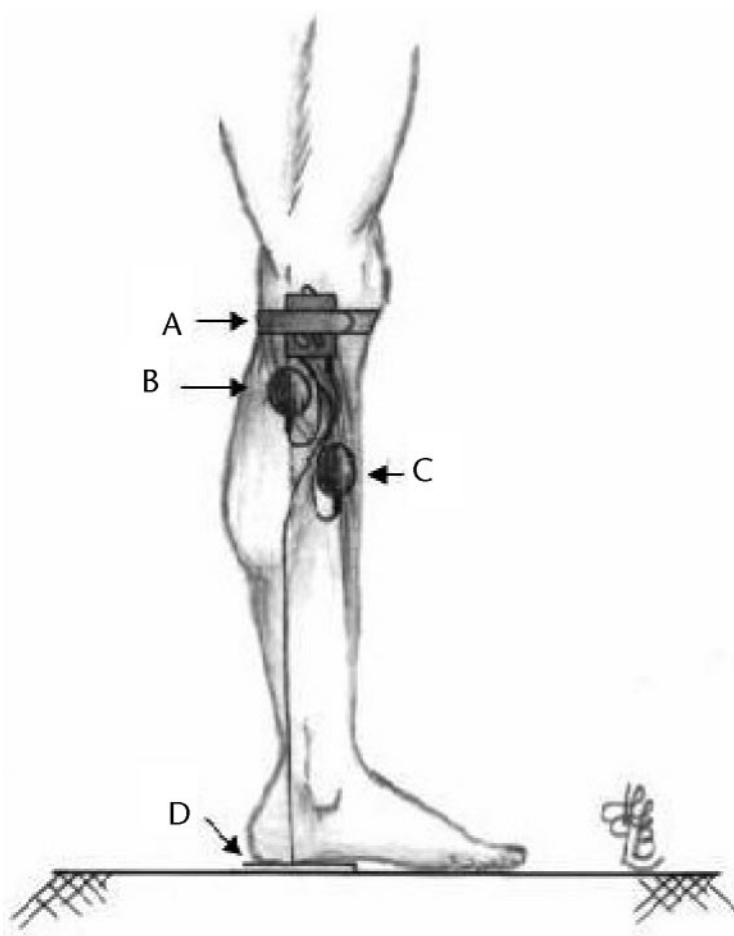


Figure 1.

Electrode positions. (A) Electronic stimulator. (B) Stimulation electrode placed at the motor point of the common peroneal nerve in the area between the popliteal fossa and the head of the fibula. (C) Electrode placed on the anterior tibialis belly. (D) Footswitch located at the heel of the affected foot, inside the shoe.

ion and eversion movements of the stimulated leg. In that situation, FES was discontinued for 5 minutes and then activated again. As volitional control improved, the FES amplitude was reduced. Treadmill training was completed after 27 sessions (3 days per week for 9 weeks), each session lasting 45 minutes.

The A₁-B-A₂ study was applied as follows: phase A₁ included gait training with BWS, phase B included gait training with BWS in combination with FES, and phase A₂ included gait training with BWS. Each of the training phases lasted 3 weeks. At the end of gait training, participants were

asked about their preference regarding the 2 interventions through open-ended questions.

A portable stimulator (Electronic Dorsiflexion Stimulator[§]) was used to stimulate the common peroneal nerve during the swing phase of the gait cycle but was not activated during the stance phase. The stimulator was equipped with an electronic control, sensors, and stimulation electrodes. Leads carried the sensor signals to the electronic control and

[§] Professor Ascendino Reis, 724 Vila Clementino-São Paulo, São Paulo, Brazil, CEP 04027-000.

stimulus current to the stimulation electrodes during the swing phase (Fig. 1). The stimulation parameters were symmetrical biphasic square waves of 150 microseconds, frequency of 25 Hz, and between 60 and 150 V, depending on subject tolerance and the level of stimulation needed to elicit robust dorsiflexion and foot eversion.

Data Analysis

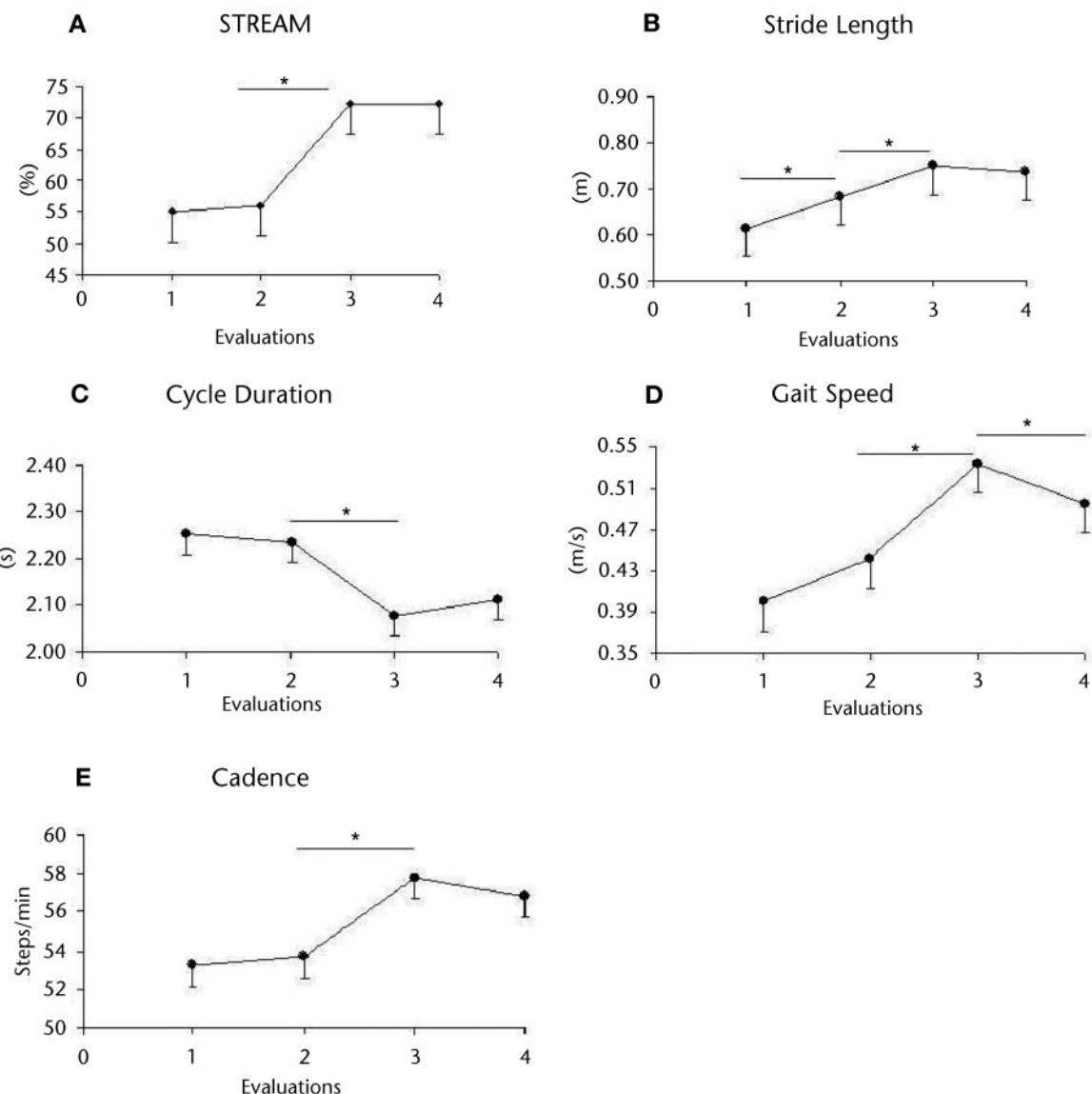
Descriptive statistics were used to compare baseline characteristics and gait scores after phases A₁, B, and A₂. An analysis of variance for repeated measures was performed to compare the main effects before, during, and after treatment for the continuous variables (gait speed, cycle duration, cadence, cycle length, duration of swing phase, duration of stance phase, and symmetry ratio). A *post hoc* Bonferroni multiple-comparisons test was used to determine differences between training phases (baseline and A₁, A₁ and B, and B and A₂). An alpha level of 5% was chosen, and GB-STAT software[¶] was used for statistical analyses.

Results

Motor Function

The percentage of motor recovery of the subjects, determined with the STREAM, showed an improvement in motor function after phase B (71%) compared with the results obtained after phase A₁ (56%) (Fig. 2A). The first assessment, carried out before the treadmill training, showed that the subjects performed $54.9\% \pm 21.9\% (\bar{X} \pm SD)$ of the items proposed by the STREAM, corresponding to 33 ± 13.2 points out of the maximum score of 60 points. After phase A₁, no significant changes were found in the STREAM data; the subjects performed $56\% \pm 21.2\%$ of the activities, corresponding to 33.6 ± 12.7 points (Fig. 2A). How-

[¶] Dynamic Microsystems Inc, 13003 Buccaneer Rd, Silver Spring, MD 20904.

**Figure 2.**

Stroke Rehabilitation Assessment of Movement (STREAM). Evaluations of gait variables were performed at the beginning of the study (1) and after each phase: A₁ (2), B (3), and A₂ (4). Horizontal bars indicate the between-phase differences. Vertical error bars represent standard deviations. Asterisks indicate significant differences between measurements ($P < .01$). (A) Mean STREAM scores with time. (B) Stride length. (C) Cycle duration. (D) Gait speed with time. (E) Cadence.

ever, after phase B, a significant increase was observed ($71\% \pm 22.6\%$), corresponding to 42.6 ± 13.6 points. After phase A₂, the subjects performed $72.3\% \pm 22.7\%$ of the activities, corresponding to 43.4 ± 13.6 points; no differences were found between phases B and A₂.

The following items changed with the training period: hip and knee

flexion in the supine position (4 subjects), hip flexion when seated (7 subjects), extension of knee when seated (3 subjects), ankle flexion when seated (6 subjects), flexion of affected knee with hip extended (3 subjects), dorsiflexion of affected ankle with knee extended (8 subjects), rising to a standing position from a seated position (7 subjects), placing of affected foot onto first step (8 subjects), taking 3 steps backward (5 subjects), taking 3 steps sideways on affected side (5 subjects), and alternating feet while walking down 3 stairs (7 subjects). Upper-limb motor activities changed slightly in 2 subjects. The raw data for the change scores are shown in Table 2. When asked about their preference for walking on the treadmill with BWS combined with FES or without FES,

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Table 2.

Stroke Rehabilitation Assessment of Movement Scores^a

Subject No.	Pretraining Scores					Scores After Phase A ₁					Scores After Phase B					Scores After Phase A ₂				
	UL	LL	BM	T	%	UL	LL	BM	T	%	UL	LL	BM	T	%	UL	LL	BM	T	%
1	14	7	10	31	51.6	14	8	10	32	53.3	20	13	15	48	80	20	13	15	48	80
2	10	12	10	32	53.3	10	12	10	32	53.3	18	16	16	50	83.3	18	16	16	50	83.3
3	11	18	15	44	73.3	11	18	15	44	73.3	12	18	17	47	78.3	13	19	17	49	81.6
4	11	11	17	39	65	11	11	17	39	65	17	19	18	54	90	17	19	18	54	90
5	18	18	18	54	90	18	18	18	54	90	18	20	19	57	95	19	20	19	58	96.6
6	7	11	14	32	53.3	7	12	14	33	55	8	16	15	39	65	8	17	16	41	68.3
7	3	7	10	20	33.3	3	7	13	23	38.3	4	8	17	29	48.3	4	9	17	30	50
8	0	3	9	12	20	0	3	9	12	20	1	5	11	17	28.3	1	5	11	17	28.3
\bar{X}	9.2	10.9	12.9	33	54.9	9.2	11.1	13.2	33.6	56.0	12.2	14.4	16	42.6	71	12.5	14.7	16.1	43.4	72.3
SD	5.8	5.3	3.6	13.2	21.9	5.8	5.2	3.4	12.7	21.2	7.2	5.4	2.4	13.6	22.6	7.4	5.4	24	13.6	22.7

^a BM=basic mobility, LL=lower limbs, T=total, % =percentage of maximum score (60 points), UL=upper limbs.

100% of subjects reported a preference for walking on the treadmill with BWS combined with FES.

Gait Parameters

A comparative analysis of the gait parameters is presented in Table 3, which shows the means and standard deviations for all of the subjects, separated into the 3 training phases. Single-limb stance duration

decreased significantly ($P=.006$) after phase B compared with phase A₁. The swing symmetry increased after phases A₁ and B compared with baseline and A₂, respectively (Tab. 3), whereas the symmetry for cycle length (obtained by dividing the unaffected cycle length by the affected cycle length and multiplying the result by 100) increased, from

84.69% to 94.26% ($P=.004$), only after phase B (Tab. 3).

The data analysis also showed a significant increase in stride length after phases A₁ and B (Fig. 2B) but no changes between phases B and A₂. Cycle duration decreased significantly after phase B, but no differences were found when phase A₁ was compared with baseline or

Table 3.
Gait Cycle Variables^a

Variable	Limb	Pretraining Score	Score After A ₁	Score After B	Score After A ₂
Stance (s)	Nonparetic	1.85±1.2	1.80±1.3 (-2.7)	1.66±1.3 ^b (-7.7)	1.69±1.3 (-2.3)
	Paretic	1.79±1.1	1.69±1.1 (-5.8)	1.58±1.2 ^b (-6.3)	1.60±1.2 (1.4)
Single-limb stance (s)	Nonparetic	1.31±0.1	1.24±0.2 (-4.8)	1.15±0.2 ^b (-7.3)	1.17±0.2 (1.4)
	Paretic	1.42±0.1	1.26±0.2 ^c (-11.8)	1.17±0.2 ^b (-7.0)	1.29±0.1 (2.3)
Swing period (s)	Nonparetic	0.37±0.14	0.43±0.17 (-17.1) ^c	0.45±0.2 (-4.5)	0.44±0.1 (1.2)
	Paretic	0.54±0.15	0.55±0.17 (2.2)	0.56±0.16 (-8.7)	0.53±0.14 (4.3)
Double-limb support (s)	Nonparetic	0.91±1.1	0.98±1.2 (8.7)	0.92±1.2 (-6.8)	0.93±1.2 (1.8)
	Paretic	0.87±1.2	0.98±1.2 (13.3)	0.92±1.3 (-6.8)	0.94±1.2 (1.1)
Stance symmetry (%)		89.89±0.1	91.44±0.2 (1.55)	89.34±0.1 (-2.10)	85.40±0.1 (-3.95)
Swing symmetry (%)		62.07±0.2	71.25±0.2 ^c (9.18)	78.17±0.2 ^b (6.92)	66.98±0.2 (-1.19)
Cycle length symmetry (%)		89.36±0.1	84.69±0.1 (-4.67)	94.26±0.1 ^b (9.58)	89.70±0.1 (-4.56)

^a Data are expressed as mean ± standard deviation. Values in parentheses are the percent differences between the pretraining scores and the scores for phases A₁, B, and A₂. No differences were found between the phase B and phase A₂ measurements.

^b Differences between the phase A₁ and phase B measurements were significant at $P<.01$.

^c Differences between the pretraining and phase A₁ measurements were significant at $P<.01$.

when phase A₂ was compared with phase B (Fig. 2C). Gait speed increased, from 0.44 ± 0.06 to 0.53 ± 0.07 m/s, after phase B ($P=.0006$) (Fig. 2D). Because cadence is linearly related to gait speed, it also increased after phase B, from 53.71 ± 6.6 to 57.75 ± 7.3 steps per minute ($P=.0006$) (Fig. 2E).

Discussion

In this study, we showed that 9 weeks of treadmill training with BWS resulted in improvements in motor function and in gait spatial and temporal variables in subjects with chronic hemiparetic stroke. However, 3 weeks of treadmill training with BWS combined with FES yielded better results with respect to cycle duration, stance, and cadence as well as cycle length symmetry. The improvement with BWS and FES was better than that obtained with BWS only.

Motor status is an important factor in gait quality and gait performance in hemiplegia and appears to be strongly dependent on the degree of motor recovery.³² The STREAM results revealed considerable improvements in lower-limb motor function and in basic mobility. The items that changed, especially an improvement in walking ability during stimulation with FES, were related to gait restoration training. Although the upper extremities did not undergo specific training, gait is a full-body activity; that fact may account for the improved STREAM outcomes. Furthermore, hand control could have been influenced by the training, because the subjects were encouraged to hold onto the horizontal bars attached to the sides of the treadmill for stability; doing so could have influenced the test results (ie, close hand from fully opened position and open hand from fully closed position).

The STREAM results indicated significant benefits for the subjects. Visintin et al¹ also reported change scores for the STREAM after 6 weeks of BWS training and after a 3-month posttraining follow-up. According to Ahmed et al,²⁹ the STREAM is preferred over other, related impairment or disability measures for monitoring recovery from stroke and focusing on the goals of immediate therapy. It can be used to monitor the reemergence of voluntary movement and basic mobility.²⁹ The subjects recruited for this study had significant gait disabilities, as profiled by the clinical measures of mobility, and all of them showed improvements not only in spatial and temporal gait variables but also in specific components of basic mobility and voluntary limb movements. It is known that dynamic and static tasks are compromised after stroke, and the results of the present study suggest that training with partial BWS and FES could change motor activities in both types of tasks. Although the results of the present study are not conclusive in this regard, we hypothesize that training with partial BWS and FES also could improve the behavioral repertoire in everyday life, because the ability to perform functional activities is dependent on a person's motor ability.^{33,34}

Increasing evidence has suggested that treadmill training in older subjects with hemiparesis improves locomotor capabilities during over-ground walking² and motor relearning, because it provides task-oriented practice of walking and active repetitive movement training.¹⁹ It has been suggested that through training, functional movements of locomotor patterns, sensory inputs, and therefore central neuronal circuits, become activated.⁷ In addition, in experiments with spinalized cats and chronic locomotor training paradigms, it was hypothesized that proprioceptive and cutaneous impulses

associated with repetitive movements may induce the activation of central pattern generators^{2,6} and long-term potentiation of the motor cortex, which in turn modify the excitability of specific motor neurons and facilitate motor learning.³⁵

According to Yan et al,³⁶ FES induces afferent-efferent stimulation, which results in limb movement plus cutaneous and proprioceptive inputs. The results of the present study revealed improvements in cycle speed, cycle duration, and cadence during phase B. Therefore, training with FES could have activated the tibialis anterior muscle, leading to increased contraction of the paretic tibialis anterior muscle and negligible co-contraction of the antagonist spastic plantar-flexor muscles—movements that tend to occur in subjects with hemiparesis. This situation could have led to the significant improvements in gait parameters during phase B. Furthermore, training with FES could be important in reminding subjects how to perform a movement properly. Therefore, it is possible that FES applied to the peroneal nerve facilitated motor relearning and improved ankle dorsiflexion.

Previous studies with FES in subjects with chronic hemiparesis²⁰ and chronic spinal cord injury³⁷ showed that gait speed was improved after a training period. Pohl et al³⁸ and Sullivan et al³⁹ also showed that when trained at faster speeds, subjects with hemiparesis could effectively improve their over-ground walking speed. In the present study, we found a statistically significant improvement in this variable; however, it may not have been clinically meaningful, because although the subjects were instructed and encouraged to walk as fast as possible, the speed was not systematically increased during each training session, as was done in the other studies. Moreover, no change in gait parameters was

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observed when phase B scores were compared with phase A₂ scores. This result may have occurred because the percentage of BWS and the treadmill speed did not change during phase A₂ (Tab. 1), because the subjects could not decrease BWS and increase gait speed without a loss in gait quality. Some researchers³⁸ have shown that speed training yields greater results when maximal, as opposed to submaximal, speeds are used. However, in the present study, we decided to preserve good gait patterns; this strategy may explain the results obtained during phase A₂. Better results might have been obtained if velocity and gait kinematics had been continually challenged during training.

The stance phase for both affected and unaffected limbs is greater in hemiparetic gait and represents a greater proportion of the gait cycle. Furthermore, the stance phase on the unaffected side is greater than that on the affected side, whereas the double-limb support phase on the affected side (the time spent in initial double-limb support on the affected side) is not greater than that on the unaffected side.⁴⁰ These alterations lead to an asymmetric pattern. The results obtained for stance phase and cycle length symmetry revealed a reduction and an increase in phase B, respectively (Tab. 3), suggesting an improvement in gait pattern.

Our motor function, cadence, and stride length outcomes are in agreement with the results of the study conducted by Hesse et al,²⁰ in which multichannel electrical stimulation combined with a treadmill was applied to subjects with hemiparesis. However, the percentage of improvement in gait speed was very different from our data; this difference may be explained by the number of muscles stimulated by FES and by the contribution of spontaneous recovery, particularly in 6 of the 11

subjects in the study by Hesse et al, whose poststroke interval was less than 6 months.

After the gait training period, the subjects noted an improvement in their gait and balance and reported being more able to perform their activities in different environments. We identified 2 main advantages of using FES combined with treadmill training. The first advantage was that all of the subjects reported a preference for walking on the treadmill with BWS combined with FES. They reported that gait training during phase B was more comfortable because it was easier to place their foot during early stance. The other advantage was that training with FES decreased the participation of the physical therapists. Manual assistance was provided to help the subjects optimize gait quality during training, and the therapists noted a decrease in their work. It was easier to assist gait and paretic limb loading during phase B, but there was no change in the number of personnel involved in training with FES.

It could be assumed that a simple intensity effect during phase B was the cause of the improvement in gait parameters. However, different intensities cannot explain the results obtained, because therapy duration, walking speed, and BWS were similar in the 3 phases.

A limiting factor of the present study was the possibility of a carryover or sequence (or both) effect from one phase to the next. However, the A₁-B-A₂ design allowed for the evaluation of the same subject during different procedures. Furthermore, this design had been chosen in previous investigations in which subjects acted as their own control subjects and did not limit the reliability of the studies.^{20,41,42} Another limitation was the small number of subjects evaluated. Despite the large

number of people with hemiparesis in rehabilitation, most were in the acute phase (less than 6 months after stroke), and the physical condition of people with chronic stroke made it difficult to find a larger group of people able to take part in all phases of this research. Furthermore, the short duration of the intervention (3-week training duration) was a limitation of the study design because it did not allow a performance plateau to be reached.

Further studies will be necessary and should focus, for example, on adding a phase B after phase A₂. Doing so would allow a comparison of the differences between phases B and A₂ in subjects with chronic stroke and better define the effect of training with FES on functional motor recovery and gait parameters in hemiplegia. Given that the changes were assessed on the day following the end of the training, it cannot be determined with certainty whether the intervention resulted in learning (retention) or in performance adaptation.

Despite these limitations, the present study provided important information about the influence of FES combined with partial BWS training in subjects with chronic hemiparesis and can help to optimize the physical therapeutic approach in stroke rehabilitation. In addition, this single-case series showed an alternative method for gait training with a treadmill and BWS that may decrease the number of personnel required to carry out the training.

Conclusion

The results of the present study indicate that people with chronic hemiparetic stroke provided with training likely would benefit from a walking program combining partial BWS and FES. Besides the well-known effects of gait training with a treadmill and partial BWS in gait restoration after

stroke, the combined use of FES applied to the common peroneal nerve and treadmill training with BWS may promote improvements in motor recovery and in the spatial and temporal variables cycle duration, stance, and cadence as well as in the cycle symmetry of hemiparetic gait. In addition, the use of FES during treadmill training was preferred by the subjects and facilitated the work of the physical therapists.

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