

# Gait Training After Stroke: A Pilot Study Combining a Gravity-Balanced Orthosis, Functional Electrical Stimulation, and Visual Feedback

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**Rationale:** This case report describes the application of a novel gait retraining approach to an individual with poststroke hemiparesis. The rehabilitation protocol combined a specially designed leg orthosis (the gravity-balanced orthosis), treadmill walking, and functional electrical stimulation to the ankle muscles with the application of motor learning principles.

**Case:** The participant was a 58-year-old man who had a stroke more than three years before the intervention. He underwent gait retraining over a period of five weeks for a total of 15 sessions during which the gravity compensation provided by the gravity-balanced orthosis and visual feedback about walking performance was gradually reduced.

**Outcomes:** At the end of five weeks, he decreased the time required to complete the Timed Up and Go test; his gait speed increased during overground walking; gait was more symmetrical; stride length, hip and knee joint excursions on the affected side increased. Except for gait symmetry, all other improvements were maintained one month post-intervention.

**Conclusions:** This case report describes possible advantages of judiciously combining different treatment techniques in improving the gait of chronic stroke survivors. Further studies are planned to evaluate the effectiveness of different components of this training in both the subacute and chronic stages of stroke recovery.

Supplemental information (videos) for this article can be found at [www.jnptextra.org](http://www.jnptextra.org)

**Key words:** gait, walking, recovery of function, robotic training, physical therapy, rehabilitation, stroke

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## INTRODUCTION

Stroke is a leading cause of disability among adults in the United States.<sup>1</sup> Individuals who have had a stroke typically undergo intensive gait retraining in the first few months after the stroke. However, even those stroke survivors that are able to walk independently after a course of physical therapy frequently have residual gait deficits, and many individuals never achieve community ambulation status.<sup>2</sup> Individuals with hemiparesis walk slower and have a slower cadence and shorter stride length compared with nonimpaired control subjects.<sup>3,4</sup> These individuals tend to spend more time in the double support phase of the gait cycle and less time in stance on the affected limb. Such deficits result in inefficient gait patterns that limit an individual's independence at home and in the community<sup>5,6</sup> and predispose them to secondary problems such as injuries from falls.<sup>7,8</sup>

Recent studies have emphasized the need for intensive walking practice after a stroke.<sup>9,10</sup> However, supervised intensive gait training is usually too expensive to be practical. Moreover, in the acute and subacute phases after a stroke, trunk instability and poor balance may make walking safety a particular concern. Recent studies have tested a variety of gait retraining interventions intended to provide the benefits of safe, intensive walking practice to participants with stroke. These include body weight-supported training,<sup>11</sup> motor imagery,<sup>12</sup> gait training with a robot-driven active gait orthosis,<sup>13</sup> and a mechanized gait trainer.<sup>14,15</sup>

In a recent editorial, Whitall<sup>16</sup> suggested that individuals with a chronic stroke (more than nine months) benefit from further training and future research on stroke rehabilitation should focus on specific questions that maximize training benefits leading to efficient and effective rehabilitation strategies. Some of the directions suggested in this editorial were combining different training programs and targeting

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specific programs toward particular patient groups. Only a few studies have evaluated the effects of combining interventions such as functional electrical stimulation (FES) and the mechanized gait trainer,<sup>17,18</sup> virtual reality coupled with robotic therapy,<sup>19</sup> and robotic therapy along with application of motor learning principles.<sup>20</sup> These studies suggest that combining different treatment strategies could make poststroke rehabilitation more efficient and effective.

In this article, we describe the findings of an initial case report to test the potential usefulness of the combination of training with a specially designed gravity-balanced orthosis (GBO), treadmill walking, FES, and principles of motor learning. Each component had a specific role in the training protocol that is described below.

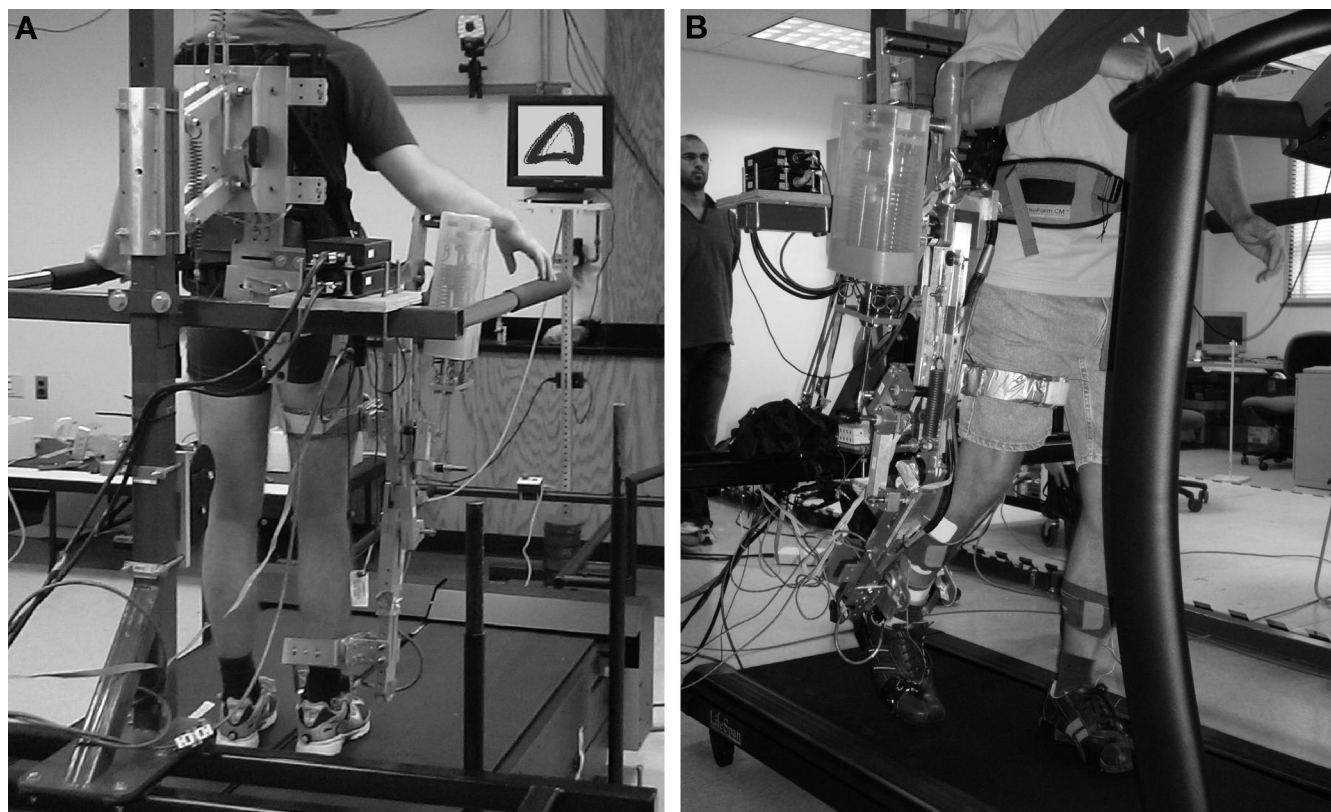
### GRAVITY-BALANCED ORTHOSIS

Robotic devices that are currently available for gait training mostly move the patient's limb through a prescribed path. This allows the patient to experience a "normal" pattern of movement without having to generate the movement on his or her own. The GBO, on the other hand, allows the patient to produce movement on his or her own while making the motion easier by reducing/eliminating the effect of gravity on the limb.

The GBO was designed to primarily assist motion at the hip and knee joints by fully or partially compensating for the

weight of the limb segments. Although gravity plays less of a role than dynamic forces during fast walking, its contribution is more important at the walking speeds produced by most individuals after a stroke.<sup>5</sup> Conceptually, removing the effects of gravity early in rehabilitation may allow patients to activate weakened muscles while they produce more normal walking patterns, limiting the typical compensations.

Details about the GBO design and applications have been reported elsewhere.<sup>21,22</sup> Briefly, the GBO is designed to assist persons with hemiparesis to walk by using a specially designed spring configuration that can completely or partially reduce the effect of gravity (Figure 1). The principle involved is as follows: (1) the center of mass of the subject's lower limb and the attached orthosis is geometrically located using a parallelogram mechanism and (2) springs are placed at suitable positions so that they completely or partially balance the effect of gravity over the entire range of joint motion. The device can be adjusted to the geometry and inertia of each subject to achieve the desired level of gravity balancing throughout the range of motion. A key feature of the device is that it is passive, eliminating the need for motors. Benefits of such a system are reduced safety concerns and drastically reduced equipment costs. From a rehabilitation perspective, the device is entirely patient driven and serves only to supplement or facilitate the movements initiated by the user.



**FIGURE 1.** The gravity-balanced orthosis (GBO). A. A subject is shown at rest in the gravity balanced orthosis, while standing on a split-belt treadmill. Note the attachment of the orthosis to the large frame at the back of the subject and the treadmill. B. Participant walking on a treadmill with the gravity-balanced orthosis during a training session. **For the video of the GBO go to [jnptextra.org](http://jnptextra.org).**

Because the GBO provided complete or partial elimination of the influence of gravity on the participant's paretic limb, thereby reducing the amount of muscle activation required to attain adequate joint excursions,<sup>22,23</sup> more extended training sessions were possible than for unassisted walking. Moreover, combining this assistance with treadmill walking allows for a high number of repetitions in a functional context, known to be required for plastic brain changes to occur.<sup>24</sup> Continuous treadmill walking can also assist cardiovascular fitness in chronic stroke survivors, which is an added benefit of the training.<sup>25</sup>

With improvements in walking performance, the amount of gravity balancing could be gradually reduced or eliminated altogether, which is an ultimate goal along with improved independent overground walking.

## FES

FES has been applied to assist functional movements such as standing,<sup>26,27</sup> walking,<sup>28–30</sup> and grasping.<sup>31</sup> In individuals with hemiparesis after stroke, stimulation of ankle dorsiflexors for the treatment of footdrop is the most common application of FES.<sup>32–40</sup> In contrast to most studies that use FES for gait training, we delivered FES not only to the ankle dorsiflexor muscles for swing phase training but also to the plantarflexor muscles to assist with push-off and the initial swing phase of knee flexion.

## Feedback for Motor Learning

Provision of adequate feedback is essential for motor learning.<sup>41</sup> During training sessions, a video monitor was placed in front of the participant at eye level to provide online knowledge of performance. Feedback consisted of real-time plots of the relative motion between the hip and knee angle throughout the gait cycle or the sagittal plane foot position (ie, instantaneous anterior-posterior vs vertical position plot). The “desired” or “ideal” joint angle motion or footpath was also displayed for the subject. Initially, this allowed the participant to visualize in real time his deviations from the desired gait pattern. However, during training sessions, this feedback was gradually withdrawn as continuous concurrent feedback is known to degrade learning.<sup>42</sup> Instead, summary feedback was provided after a trial of multiple gait cycles (see Methods section).

In the current approach, a team of professionals, including physical therapists, a biomechanist, and engineers worked together to design and build the GBO and FES system used for training. The physical therapists took the lead in designing and implementing the training, whereas the engineers took the lead in developing and assembling the hardware and software used during training. Our goal in combining GBO, FES, and motor learning principles was to determine whether the patient could achieve an increased stride length on the hemiparetic side, improved gait symmetry, increased motion of both hip and knee joints, faster gait speed, and increased weight bearing on his impaired right side.

## CASE REPORT

### Participant

The participant in this case report was a 58-year-old man who was left-hand dominant before a left middle cerebral artery infarction. He had a single stroke three years and five months before this training. He gave informed consent to participate in this training based on procedures approved by the Human Subjects Review Board at the University of Delaware.

The participant's stroke led to infarcts in the left basal ganglia, internal capsule, corona radiata, and posterior left temporoparietal lobe. Immediately after the stroke, he spent five days in acute care followed by three weeks of rehabilitation including physical, occupational, and speech therapy. He continued physical therapy on an out-participant basis two to three times a week for the first year after the stroke, with some breaks in between. For three years after the stroke, the participant also volunteered in the laboratory section of a neurological rehabilitation class for physical therapy students, where he received additional motor training once per week for 10 weeks each fall semester.

Before his stroke, the participant held a full-time engineering job. His height and weight were 1.75 m and 74.8 kg, respectively. At the time of this report, he had retired and was no longer undergoing therapy. His exercise activity included regular walks in the neighborhood around his home without the assistance of any orthotic device or a walking aid. He reported being independent in all activities of daily living. However, observational analysis revealed a gait that was slower than normal for his age and asymmetrical. He had difficulty clearing the ground with the affected foot, and used compensatory patterns such as hip elevation and circumduction. Because of the increased effort required to walk, he reported limiting his walking to less than he would like. The participant's goal from this intervention was to improve his ability to walk on uneven outdoor surfaces so that he could take longer walks for exercise.

### Baseline Examination

#### Clinical Assessment

A detailed baseline clinical assessment was performed before the start of training. The participant had good sensation on the affected side and no major cognitive deficits. He had normal perceptual abilities as determined by the motor-free visual perception test.<sup>43</sup> His performance score on other tests performed at baseline are listed in Table 1. The Mini-Mental State Examination<sup>44</sup> and the Modified Ashworth

**TABLE 1.** Scores of Evaluations Administered Before Training

Evaluations	Scores
Mini-Mental State Examination score	30/30
Modified Ashworth Scale: ankle	1+
Timed Up and Go	15 sec
Modified Fugl-Meyer, lower extremity portion	28/36
Berg Balance Scale	56/56

Scale<sup>45</sup> were administered only at baseline assessment. The Berg Balance Scale (BBS),<sup>46</sup> lower extremity portion of the modified Fugl-Meyer assessment,<sup>47</sup> and the Timed Up and Go test<sup>48</sup> were repeated at the end of training.

### Gait Analysis

Gait analysis was performed before training (pretraining), midway through training (midtraining), at the end of training (post-training), and one month after training ended (follow-up). Gait analysis was performed both during overground walking (without the GBO) and during walking on the treadmill (both with and without the GBO). This report focuses on the overground evaluation without the GBO because of its greater functional significance.

Gait data were collected at 120 Hz using a six-camera Motion Analysis Corporation system and processed using an automated real-time motion analyses system (Eva real-time version 4.3). A modified version of the Helen Hayes marker set consisting of 23 tracking retroreflective markers was used during testing. Ground reaction force data were collected using two force plates embedded in an instrumented custom-built split-belt treadmill (Bertec Corporation, Columbus, OH), both during treadmill and overground walking. Analog data were collected at 2400 Hz, and kinetic data were normalized to body mass. Foot switches were placed under the heel and the forefoot to capture heel strike and toe-off during walking.

For the overground walking trials, the participant walked at his comfortable walking speed over a walkway that included the force plates embedded in the treadmill that was at the center of the walkway. The trials that had good force plate contact by at least one foot were noted and used for further processing. Five “good” trials with force plate contact by each foot were collected. Each of these trials included two to three complete gait cycles, although ground reaction force information was limited to one cycle.

### Isometric Muscle Performance Testing

The participant also underwent isometric muscle performance testing before and after training. The ankle dorsiflexor and plantarflexor muscles were evaluated with the subject positioned on an isokinetic dynamometer (KinCom III 500-11, Chattecx Corporation, Chattanooga, TN) with the hips and knees extended. The axis of the ankle joint was aligned with the axis of the force transducer. The ankle was positioned in 15 degrees of plantarflexion for testing the dorsiflexors and at 0 degree (neutral ankle position) for testing the plantarflexors. The distal portion of the foot, the distal and proximal portions of the leg, and the distal portion of the subject’s thigh were stabilized using inelastic Velcro straps (Figure 2). Self-adhesive surface electrodes were attached on the skin over the dorsiflexor and plantarflexor muscle groups. Details about electrode placement are provided in the “Setup for FES” subsection. After ensuring appropriate electrode placement, the twitch interpolation technique<sup>49,50</sup> was used to estimate the degree of central activation. Because the participant was unable to produce a measurable volitional isometric force from the dorsiflexors, the twitch interpolation technique was tested only on the

plantarflexor muscles. First, a twitch with 600- $\mu$ sec pulse duration and 135-V amplitude was delivered to the muscle as the participant relaxed and the peak force produced recorded as the resting twitch force. Next, the participant volitionally contracted his plantarflexor muscles to generate a maximum voluntary isometric contraction (MVIC). During the MVIC, another twitch with the same pulse duration and amplitude as the resting twitch was delivered to the muscle. The increment in the MVIC force produced by the superimposed twitch was recorded as the interpolated twitch force. The resting and interpolated twitch forces were used to obtain a measure of volitional activation, the central activation ratio (CAR), as follows:

$$CAR = \left[ 1 - \frac{\text{Interpolated twitch amplitude}}{\text{Resting twitch amplitude}} \right]$$

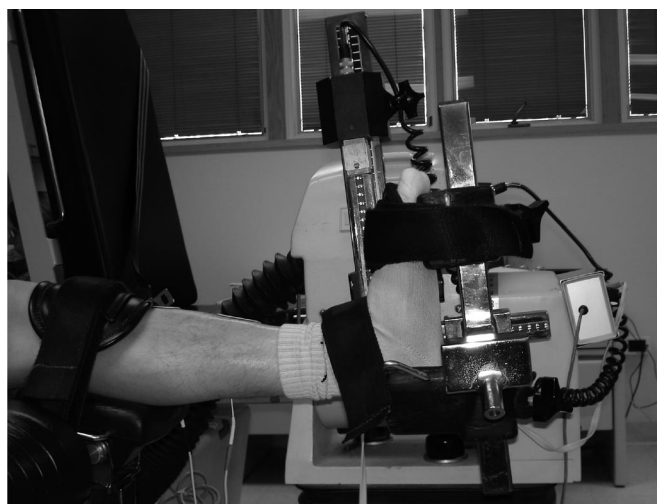
Also, the maximum voluntary isometric force was divided by the CAR to obtain the estimated maximum force generating ability of the muscle.

### Intervention

The participant trained three days per week for five weeks. Each session lasted approximately two hours, including setup time and rest periods. The participant walked about 40 minutes during each session, which included four 10-minute blocks of treadmill walking. After each block, the participant was allowed to rest while sitting on a stool and his blood pressure was monitored.

### GBO

During the training sessions, the participant walked on a treadmill (TR 2500-HRC, LifeSpan Fitness, Park City, UT) with the GBO. The GBO was attached to the participant by



**FIGURE 2.** Isometric ankle muscle performance testing. Testing position for the dorsiflexor and plantarflexor muscles on the KinCom apparatus. The subject was seated with the hip and knee extended and the ankle at 15 degrees of plantarflexion for testing the dorsiflexors and at 0 degree (neutral ankle position) for testing the plantarflexors.

cuffs strapped to the pelvis, thigh, and lower leg, and by an insert that fits into the user's shoe (Figure 1). The GBO is mounted on a walking frame behind the treadmill. A harness was attached overhead to the walking frame to prevent falling should the patient lose his or her balance. A large metal plate connected the pelvic band to the walking frame to counter the forces generated by the patient's movements. The participant's right (affected) arm was suspended in a sling because there was not adequate room for him to swing the arm during walking. However, the participant showed very little arm swing during overground walking, as is often the case with individuals after a stroke. The participant held the treadmill's handrails only when the treadmill speed was changed.

### Setup for FES

Both dorsiflexor and plantarflexor muscle groups were stimulated using a real-time FES system consisting of a real-time controller (NI cRIO-9004), analog input module (NI9210), digital input/output module (NI9401), and Grass S8800 stimulator. Foot switches placed on the heel and toe of each foot were used to detect the different phases of gait during treadmill walking. Custom written software (LabVIEW, National Instruments, Austin, TX) was used to acquire the foot-switch data. Electrical stimulation was delivered via self-adhesive electrodes (TENS Products, Grand Lake, CO; two  $\times$  two-inch square foam for dorsiflexors; three-inch Round Tricot for plantarflexors). For the dorsiflexors, the cathode electrode was placed over the motor point of the tibialis anterior (TA) and the anode was placed over the muscle belly at the distal portion of the anterolateral aspect of the leg. TA electrode placement was adjusted to ensure that negligible eversion/inversion ankle movements were produced during stimulation. For the plantarflexors, the cathode was placed over both the medial and lateral heads of the gastrocnemius (MG-LG); the anode was placed over the distal portion of the gastrocnemius muscle belly. Stimulation amplitude for the TA was set with the participant seated with his leg suspended so that the ankle was hanging freely in a plantar-flexed position. The train duration was set at 300 msec and the pulse duration at 300  $\mu$ sec. The stimulation train began with an initial triplet (ie, three pulses, each separated by five milliseconds) and the remaining pulses were separated by a 33-msec interpulse interval (30 Hz). The initial high frequency burst was used to take advantage of the catchlike property of the muscle.<sup>51</sup> The stimulation amplitude was then increased gradually until a dorsiflexion movement to neutral ankle position (0 degree) was produced without significant eversion and inversion. Stimulation amplitude for MG-LG was set with the participant standing and bearing weight on both limbs. Similar stimulation parameters to those used for the TA were used, except the train frequency was 100 Hz and pulse duration was 600  $\mu$ sec. The stimulation amplitude was then increased until we observed the heel lifting off the ground or the subject identified the maximum tolerable amplitude. In the present report, the participant was able to tolerate the levels of stimulation required to lift the heel off the ground. Because the pulse amplitude was not varied during the session and the frequency and pulse duration used to set the amplitude were the highest frequency and

pulse duration used for activation of either muscle during the training sessions, we were assured that the subject would be able to tolerate the stimulation. For both muscles, the 30-Hz train frequency and 300- $\mu$ sec pulse duration were the initial stimulation parameters. The stimulation frequency and intensity (via pulse duration) were increased in the training session to generate the desired responses from both muscles and to compensate for any fatigue that developed during the session. The participant had no difficulty tolerating the stimulation either when setting the amplitude or when the stimulation parameters were changed during treadmill walking. The dorsiflexor muscle group was stimulated from toe-off to heel strike of the paretic limb. Plantar-flexor stimulation was timed to start at heel strike of the nonparetic limb, which coincided with terminal stance for the paretic leg. The FES system terminated plantarflexor stimulation when toe-off of the paretic leg was detected.

### Visual Feedback

In the current report, the desired motions were based on patterns exhibited by five healthy volunteers walking in the GBO with 0% balancing (ie, no assistance from the device). The data were scaled to the participant's segment lengths to produce an appropriate foot trajectory template. The template was used as a target that the participant attempted to match during practice. Visual feedback was provided either in the form of plots of hip angle versus knee angle motion (in degrees) or of the sagittal plane foot motion (in centimeters) of the hemiparetic leg. During early training, continuous real-time visual feedback was provided to the participant. Over training sessions, the continuous feedback was reduced and gradually taken away. At the end of each block of walking for all training sessions, summary feedback was provided about the performance over several gait cycles during the previous block relative to the hip-knee angle or sagittal plane footpath. At the beginning of every training session, the participant was shown a figure with his performance in the previous sessions (including baseline) versus the required template. This way, the participant could see whether there was an improvement in performance over successive sessions.

### Protocol

Initial training had the participant walking at his self-selected walking speed (1.5 miles/hr or 0.67 m/sec), determined during the initial gait evaluations. The speed was gradually increased over sessions to the participant's tolerance, reaching a maximum of 1.9 miles/hr (0.85 m/sec) by the end of training. Training began with full (100%) gravity balancing of both the leg and device. Gradually, over several sessions, the gravity balancing of the leg was reduced to 75%, 50%, 25%, and finally 0% gravity balancing, whereas the device was always 100% gravity balanced (ie, the device itself was always gravity neutral so that the user would not "feel" the mass of the device). Table 2 shows the schedule of training in detail, including the level of gravity balancing, use of FES, and visual feedback at each training session, and the timing of the evaluation sessions. The follow-up evaluation

**TABLE 2.** Training Protocol

Evaluation Session	Training Day	% Gravity Balanced	FES	Feedback			Foot/Joint
				Continuous	Intermittent	Summary	
Pre-training	1	100	—	x		x	Foot
	2	100	—	x		x	Joint
	3	100	—		x	x	Foot
	4	100	PF	x (early)	x (late)	x	Foot
	5	100	PF/DF		x	x	Joint
	6	100	PF/DF		x	x	Foot/joint
Mid-training	7	75	PF/DF		x	x	Foot/joint
	8	75	PF/DF		x	x	Joint
	9	50	PF	x (early)	x (late)	x	Joint
	10	50	PF/DF		x	x	Foot/joint
	11	50	PF/DF			x	Joint
	12	25	PF/DF			x	Joint
	13	25	PF/DF			x	Joint
	14	0	PF/DF			x	Joint
	15	0	PF/DF			x	Joint
Post-training							

Abbreviations: FES, functional electrical stimulation; PF, plantarflexors (medial and lateral gastrocnemius); DF, dorsiflexors (tibialis anterior).

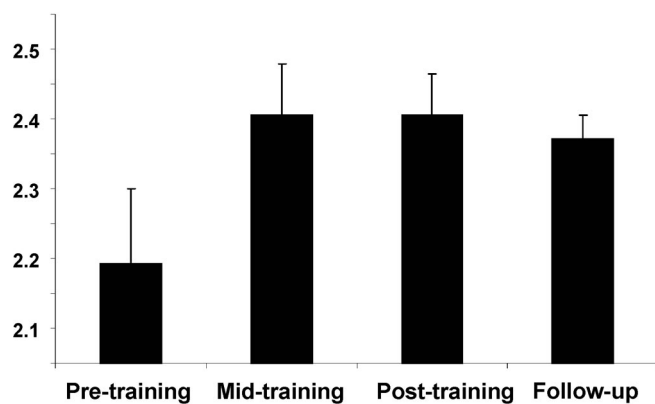
Early and late refer to the first half (blocks 1 and 2) and second half (blocks 3 and 4) of each training session. Please note that the device always gravity-balanced the mass of the gravity-balanced orthosis, so that the user would not “feel” the mass of the device.

session is not shown as it was performed a month after the final training session.

**Outcomes**

**Clinical Assessment**

The only clinical measure that showed improvement from the pretraining evaluation to the posttraining evaluation was the participant’s score on the Timed Up and Go test. By the end of training, the participant’s time had dropped to nine seconds compared with his time of 15 seconds before training, a 40% improvement in performance. The posttraining time was within the normal range for adults without neurological impairment who are independent with balance and mobility skills.



**FIGURE 3.** Gait speed in miles per hour across the four evaluation sessions. SD bars across gait cycles are shown.

**Gait Evaluation**

**Overground walking**

Gait speed showed a marginal improvement over training, increasing by 10% from the pretraining to post-training (Figure 3). This improvement was maintained at the one-month post-training follow-up evaluation.

To test for the effect of training on gait symmetry, we calculated the ratio of the stance time to swing time for each leg. As expected, the ratio was very asymmetrical pretraining, with the stance to swing ratio being much lower on the impaired side (Table 3; 1.2 on affected side vs 2.0 on the unaffected side). Immediately post-training, a more symmetrical gait pattern was seen (1.6 vs 1.8), which was due to decreases in the ratio for the unimpaired side as well as an increase in the ratio on the impaired side. However, this training effect was lost completely by the one-month follow-up evaluation, with a substantial increase in the ratio on the unimpaired limb. This result suggests that although there was an initial adaptation to the training, the changes that lead to greater gait symmetry were not learned.

There was an increase of approximately 20% in excursion of the hip (from 33.2 to 39.7 degrees) and approximately 9% of the knee (from 24.8 to 27.2 degrees) post-training during the swing phase of gait (Figure 4), which continued to increase at the one-month follow-up evaluation. In addition, the amount of plantarflexion at initial foot contact decreased over the training period, although the ankle was still less than neutral at the end of training (8.3 to 4.6 degrees of plantarflexion from pre- to post-training, Table 4). The amount of plantarflexion during swing also decreased by the one-month follow-up evaluation (2.8 degrees of plantarflexion). Other changes in joint motion were less systematic or not main-

**TABLE 3.** Gait Symmetry Across Training Sessions

	Pretraining		Midtraining		Post-training		Follow-up	
	Affected	Unaffected	Affected	Unaffected	Affected	Unaffected	Affected	Unaffected
Stance time (% of gait cycle)	0.55	0.67	0.61	0.65	0.62	0.64	0.58	0.71
Swing time (% of gait cycle)	0.45	0.33	0.39	0.35	0.38	0.36	0.42	0.29
Stance/swing ratio	1.2	2.0	1.6	1.9	1.6	1.8	1.4	2.4

tained. Finally, step length of the affected foot during the swing phase was estimated by calculating the distance traveled by the ankle marker in the sagittal plane. This measure was chosen because the greatest effect of the GBO was expected to be on the hip and knee of the affected side during swing. This distance not only increased post-training by about 10% (from 101.2 to 111.2 cm), but also remained higher at the one-month follow up, suggesting that the participant had learned to take longer steps on the affected side.

### Changes in Ground Reaction Forces

The vertical ground reaction forces on the affected side in the posttraining and follow-up evaluations were higher than at the pretraining evaluation, suggesting that the participant learned to take more weight on the affected limb (Figure 5). Although the peak ground reaction force increased from 830.67 N pre-training to 937.95 N mid-training, it decreased again at the posttraining evaluation (858.9 N), and then increased again by the one-month posttraining evaluation (899.83 N). There was, therefore, a general upward trend. However, because the highest value occurred midtraining, the reliability of this improvement is uncertain.

### Changes in Isometric Muscle Performance

After training, the MG-LG MVIC showed a 46.4% increase (pre-training = 207.8 N, post-training = 304.24 N); the CAR showed a 9.21% increase (pre-training = 0.51,

post-training = 0.55); the estimated maximum force generating ability of MG-LG showed a 34% increase (pre-training = 410.49 N, post-training = 549.97 N).

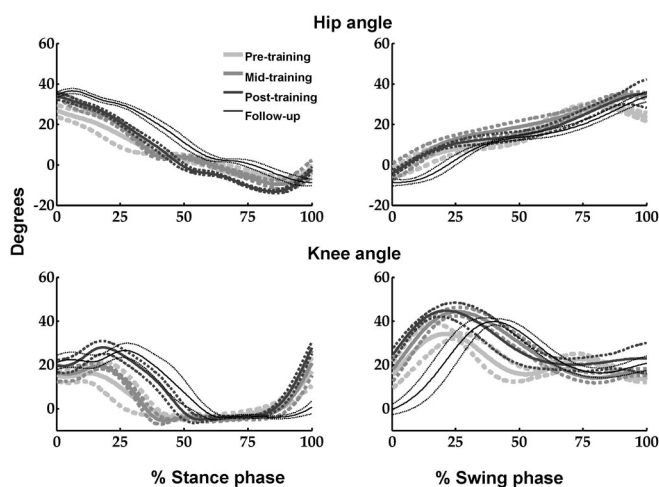
### Subjective Feedback from Participant After Training

The participant reported tolerating the training protocol well. During the training sessions, the participant reported being more “aware” of his gait and was “conscious” of whether his foot was clearing the ground adequately, bending his knee adequately during swing, or transporting his affected foot farther forward. After training, the participant reported feeling that he walked faster during overground walking and that his foot was catching less on the ground during normal activities. He specifically reported that he was more confident walking in his neighborhood over uneven terrain and was spending more time doing so.

### DISCUSSION

This case report provides a preliminary evaluation of the effectiveness of a poststroke gait retraining intervention that involved the simultaneous application of a gravity-balanced orthotic device, FES, and visual feedback. Overall, the training regimen was well tolerated by the participant. Some of our predictions were supported by quantitative changes in gait during this report. The time required to perform the Timed Up and Go decreased; there was an increase in the distance covered by the impaired side during swing, the speed of walking, weight-bearing on the impaired limb, and knee and hip joint excursions. All these parameters were also maintained during the one-month follow-up. There was also 46% increase in MVIC of MG-LG. Unfortunately, although the participant’s gait was more symmetrical after the five-week training, this symmetry was not maintained at the one-month evaluation post-training.

These results are encouraging for an initial case report evaluating the effectiveness of our novel approach. For most of our outcome measures, the minimal clinically important difference are not known. One standardized test that did show a difference post-training was the Timed Up and Go. Although minimal clinically important difference or cutoff scores are not known for the stroke population, a score of  $\geq 14$  seconds is suggestive of a high risk of falls in community-dwelling older adults.<sup>52</sup> Adults without neurological impairments who are independent with balance and mobility skills are able to perform the test in  $< 10$  seconds.<sup>53</sup> Thus, at the beginning of this case report, the participant was at risk of falls based on this criterion (15 seconds), but after the training, he was able to perform the test in the same time as adults without neurological impairments (nine seconds).



**FIGURE 4.** Average hip and knee angle motion ( $\pm$ SD) during the stance and swing phases during each of the four evaluation sessions. Positive angles correspond to flexion motion and negative angles correspond to extension motion.

**TABLE 4.** Overground Walking Parameters

		Evaluations			
		Pre-training	Mid-training	Post-training	Follow-up
Hip flexion excursion—swing (degree)	Mean	<b>33.2</b>	38.0	39.7	<b>42.9</b>
	SD	2.3	3.8	7.6	2.1
Hip abduction excursion—swing (degree)	Mean	10.7	13.2	14.1	9.5
	SD	1.3	0.5	1.4	0.6
Peak hip extension angle (–)—stance (degree)	Mean	–7.9	–9.9	–13.3	–9.0
	SD	0.8	2.5	0.8	1.9
Knee flexion excursion—swing (degree)	Mean	<b>24.8</b>	30.7	27.2	<b>40.9</b>
	SD	4.7	2.9	2.7	2.7
Ankle position [PF(–)/DF(+)] at initial contact (degree)	Mean	–8.3	–7.1	–4.6	–2.8
	SD	2.3	0.8	1.0	2.2
Path length of foot—swing (cm)	Mean	<b>101.2</b>	109.2	111.2	<b>109.9</b>
	SD	4.4	3.1	2.2	2.2

The bold values indicate the measures that showed the most change from the pre-training to the post-training measurements and were maintained during follow-up. Abbreviations: PF, plantarflexors (medial and lateral gastrocnemius); DF, dorsiflexors (tibialis anterior).

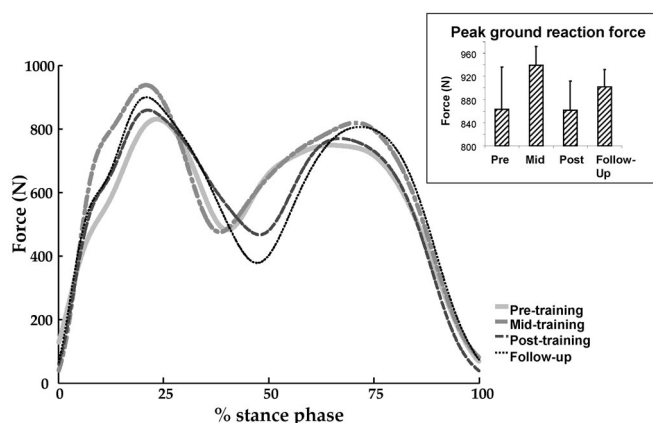
Results of this preliminary investigation compare favorably with those of previous studies examining the effects of novel gait retraining programs.<sup>11–14,18</sup> Studies that used a single treatment intervention showed an improvement in some parameters such as gait speed and balance.<sup>11,12,14,18</sup> This was sometimes accompanied by other improvements such as a decrease in double support time or increase in stance time.<sup>12,13</sup> However, some of these studies were performed within the first few months after stroke<sup>14,18</sup> making it difficult to rule out spontaneous recovery as one of the factors contributing to improvement in performance. Further, another difference of our approach is to address specific clinical problems with targeted treatments. For example, patients who have difficulty in producing adequate hip and knee flexion during swing would benefit from using the GBO and those with inadequate plantar- and/or dorsiflexor strength would likely benefit from addition of FES. An important difference to point out between the GBO and other robotic devices used in other studies is that the GBO does not move the patient's

limb through a predetermined pattern, but instead makes it easier for the patient to move by reducing the effects of gravity.

In our report, the participant's balance before training was normal based on his performance on the BBS, so we did not expect changes in balance with training. Recently, a ceiling effect has been noted with the BBS in community-dwelling older adults<sup>54</sup> and chronic stroke survivors.<sup>55</sup> Thus, in future studies, we would consider using alternate tests for balance, such as the Postural Assessment Scale for Stroke Patients, which did not show such a ceiling effect.<sup>55</sup>

The participant was an independent ambulator before the intervention, but his gait was awkward. Although we did not specifically measure energy cost, the participant reported fatiguing quickly after walking for short distances, which restricted his walking. In addition, he had developed several gait compensations. After the training, he voluntarily reported that he was able to walk longer distances without fatiguing and that he tripped less. The reported decrease in fatigue is consistent with previous studies showing that treadmill training improves cardiovascular fitness in chronic stroke survivors.<sup>25</sup> The results of this case report are promising in that changes in walking of this chronic stroke survivor occurred after a five-week period of intensive training. This report adds support to the recent idea that with appropriate intervention, even chronic participants may improve performance.<sup>11</sup> An important future issue is to determine whether individuals with subacute stroke can also achieve improvements in their walking with the present training. We believe that this mode of treatment may be more effective in such persons if applied intensively because it may help limit the gait compensations that such persons typically develop when attempting to ambulate, whereas selective muscle weakness is a significant problem.

Another issue that needs to be studied further is why some parameters such as gait symmetry were not retained in the one month after training. It may be that the asymmetries developed by the participant were too ingrained over the three



**FIGURE 5.** Average ground reaction forces measured from the force platform during the stance phase of walking at each of the four evaluation sessions. The inset shows the peak ground reaction force with SD bars.



plus years of functional walking after his stroke to be permanently affected without more intensive training than the five weeks provided here. Spending more time training at the lower levels of gravity balancing (25% and 0%) at the end of training may have been beneficial in this regard. We were unable to extend the training beyond this period because of the participant's personal constraints.

In this report, the GBO was used to train motion of the hip and knee joints. Problems in controlling the ankle were addressed by adding FES to the ankle muscles. We took this approach because patients after a stroke frequently have greater impairment of muscles of the distal limb. A long-term goal of this work is to build a portable stimulator so that participants who require FES to substitute for the lack of voluntary muscle activation at the ankle will have a device that they can use permanently. Portable FES systems could provide a means for controlling ankle muscles during daily activities.<sup>38,56-59</sup> In contrast, a portable system to help control the hip or knee joints is more difficult, particularly regarding comfort (eg, stimulating the hamstrings is typically very uncomfortable). Thus, the GBO in combination with motor learning through feedback and structured practice was designed to help the participant improve the control of the hip and knee joints, as well as the overall foot trajectory. Improvement of knee and hip flexion during swing, in turn, will reduce the amount of ankle dorsiflexion required to clear the foot during walking.

A recent meta-analysis of literature showed that FES produces improvements in muscle strength post-stroke.<sup>60</sup> Interestingly, the MG-LG MVIC, CAR, and estimated maximum force generating all showed considerable increases with training, suggesting that our training approach probably increased the muscle's force generating ability, both volitionally and in response to stimulation. Because no specific muscle training was performed in this report, we speculate that the functional strength improvements were related to the practice with gradually increasing difficulty as gravity balancing was reduced, in combination with the FES. The question remains, however, whether similar increases in muscle strength could be obtained by FES alone or in combination with a similar intensity of treadmill training alone.

Similar questions can be raised about the measured changes in overground walking speed and movement kinematics. However, it is noteworthy that each time the gravity compensation was reduced, it took some time for the participant to recover the ability to approximate the required templates, suggesting that practice in the reduced gravity environment helped the participant develop improved control of his foot trajectory.

One of the strengths of this training approach is that continuous practice of walking can be provided along with on line visual feedback and summary feedback after multiple walking cycles. The participant was able to see his performance with respect to the prescribed trajectories and his improvement in performance within and across training sessions. This was motivational for the participant. We used known principles of motor learning, in combination with practical considerations, to design the practice and feedback provided during training. However, future work will need to

determine how to optimize the training and feedback to achieve better results. For example, although summary feedback has been shown to be better than continuous feedback to enhance learning in healthy subjects learning to parameterize relatively simple tasks,<sup>61</sup> it is unclear whether summary, faded or continuous feedback might be more effective to enhance learning of motor patterns by patients with motor impairments, particularly in the early phases of learning.<sup>62,63</sup>

This case report is an initial test of a novel training protocol. Although several of the measured variables showed a change in the direction of improvement, none except the Timed Up and Go has established norms that can be used to demonstrate clinical change. As already discussed, there could have been a ceiling effect of the BBS in this patient. This is a limitation of this report and future studies should include other tests that are more sensitive. Another limitation of the report is that the GBO in its current form is not yet ready for clinical use. The current prototype is a research prototype. It requires the engineers to make adjustments in settings of the springs and links to adjust the device for a given subject and also for different levels of gravity balancing. However, it serves as a proof of concept. Future versions of the GBO will address these issues to make it user friendly. The advantage of the device is that it makes it easier for the patient to voluntarily control their impaired leg without the typical compensations, allowing the practice of movements that better approximate "normal." From a financial point of view, it would be much cheaper than many motor-driven robotic devices because it does not consist of any powered elements. By making therapy more automated, gravity-balanced gait training may allow therapists to train several patients simultaneously with less physical effort by the therapist. These predictions obviously require more extensive investigation.

The current case report served to show the feasibility of using the GBO in conjunction with FES and visual feedback as a gait-training paradigm, thereby providing a framework for designing future studies. Future, controlled studies are planned with small groups of patients receiving training for similar lengths of time with only the GBO or FES, with both GBO and FES, and a control group receiving walking practice on a treadmill without the GBO or FES. Another question that needs to be resolved in future work is whether the improvements observed were due the specific training or resulted from a general increase in strength that could be achieved with methods involving intensive gait training. The data from the current report cannot answer this question. However, the participant was a relatively young, active individual. Thus, it is less likely that strength improvements per se played the primary role in his gait improvements. One way that we plan to control for this in future work is to have patients engage in an intensive strength training protocol before commencing gait training.

## SUMMARY

In this case report, we applied a novel training approach to a chronic stroke survivor that included combining a GBO, FES, and motor learning principles to improve walking performance. This approach was found to be feasible and

showed positive effects on the participant's gait after a five-week training period. Advantages of this training approach are that training parameters including feedback can be precisely computer controlled and accurate data can be generated that the therapist can use to monitor progress within and across sessions. Future research will be required to determine the effectiveness of different components of this training in both the subacute and chronic stages of stroke recovery.

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## REFERENCES

- Rosamond W, Flegal K, Friday G, et al. Heart disease and stroke statistics—2007 update: a report from the American Heart Association Statistics Committee and Stroke Statistics Subcommittee. *Circulation*. 2007;115:e69–e171.
- Mayo NE, Wood-Dauphinee S, Ahmed S, et al. Disabling following stroke. *Disabil Rehabil*. 1999;21:258–268.
- Brandstater ME, de Bruin H, Gowland C, et al. Hemiplegic gait: analysis of temporal variables. *Arch Phys Med Rehabil*. 1983;64:583–587.
- Olney SJ, Richards C. Hemiparetic gait following stroke, part I: characteristics. *Gait Posture*. 1996;4:136–148.
- Perry J, Garrett M, Gronley JK, et al. Classification of walking handicap in the stroke population. *Stroke*. 1995;26:982–989.
- Detrembleur C, Dierick F, Stoquart G, et al. Energy cost, mechanical work, and efficiency of hemiparetic walking. *Gait Posture*. 2003;18:47–55.
- Diller L, Weinberg J. Evidence for accident-prone behavior in hemiplegic patients. *Arch Phys Med Rehabil*. 1970;51:358–363.
- Nyberg L, Gustafson Y. Patient falls in stroke rehabilitation. A challenge to rehabilitation strategies. *Stroke*. 1995;26:838–842.
- Malouin F, Potvin M, Prevost J, et al. Use of an intensive task-oriented gait training program in a series of patients with acute cerebrovascular accidents. *Phys Ther*. 1992;72:781–789; discussion 789–793.
- Richards CL, Malouin F, Wood-Dauphinee S, et al. Task-specific physical therapy for optimization of gait recovery in acute stroke patients. *Arch Phys Med Rehabil*. 1993;74:612–620.
- Miller EW, Quinn ME, Seddon PG. Body weight support treadmill and overground ambulation training for two patients with chronic disability secondary to stroke. *Phys Ther*. 2002;82:53–61.
- Dunsky A, Dickstein R, Marcovitz E, et al. Home-based motor imagery training for gait rehabilitation of people with chronic poststroke hemiparesis. *Arch Phys Med Rehabil*. 2008;89:1580–1588.
- Husemann B, Muller F, Krewer C, et al. 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, Uhlenbrock D. A mechanized gait trainer for restoration of gait. *J Rehabil Res Dev*. 2000;37:701–708.
- Hesse S, Werner C, Uhlenbrock D, et al. An electromechanical gait trainer for restoration of gait in hemiparetic stroke patients: preliminary results. *Neurorehabil Neural Repair*. 2001;15:39–50.
- Whitall J. Stroke rehabilitation research: time to answer more specific questions? *Neurorehabil Neural Repair*. 2004;18:3–8; author reply 9–11.
- Tong RK, Ng MF, Li LS. Effectiveness of gait training using an electromechanical gait trainer, with and without functional electric stimulation, in subacute stroke: a randomized controlled trial. *Arch Phys Med Rehabil*. 2006;87:1298–1304.
- Tong RK, Ng MF, Li LS, et al. Gait training of patients after stroke using an electromechanical gait trainer combined with simultaneous functional electrical stimulation. *Phys Ther*. 2006;86:1282–1294.
- Mirelman A, Bonato P, Deutsch JE. Effects of training in robot virtual reality system vs a robot alone on the gait of individuals post stroke. *Stroke*. In press.
- Ferraro M, Palazzolo JJ, Krol J, et al. Robot-aided sensorimotor arm training improves outcome in patients with chronic stroke. *Neurology*. 2003;61:1604–1607.
- Agrawal SK, Banala SK, Fattah A, et al. Assessment of motion of a swing leg and gait rehabilitation with a gravity balancing exoskeleton. *IEEE Trans Neural Syst Rehabil Eng*. 2007;15:410–420.
- Banala SK, Agrawal SK, Fattah A, et al. Gravity-balancing leg orthosis and its performance evaluation. *IEEE Trans Robotics*. 2006;22:1228–1239.
- Benoit D, Krishnamoorthy V, Banala SK, et al. An integrated approach for improving gait in a stroke population: combining robotics, FES and neuromusculoskeletal modeling. Presented at: Annual Meeting of American Society of Biomechanics, Blacksburg, VA, 2006.
- Nudo RJ. Mechanisms for recovery of motor function following cortical damage. *Curr Opin Neurobiol*. 2006;16:638–644.
- Macko RF, Ivey FM, Forrester LW, et al. Treadmill exercise rehabilitation improves ambulatory function and cardiovascular fitness in patients with chronic stroke: a randomized, controlled trial. *Stroke*. 2005;36:2206–2211.
- Bajd T, Kralj A, Segal J, et al. Use of a two-channel functional electrical stimulator to stand paraplegic patients. *Phys Ther*. 1981;61:526–527.
- Bajd T, Kralj A, Turk R. Standing-up of a healthy subject and a paraplegic patient. *J Biomech*. 1982;15:1–10.
- Agarwal S, Kobetic R, Nandurkar S, et al. Functional electrical stimulation for walking in paraplegia: 17-year follow-up of 2 cases. *J Spinal Cord Med*. 2003;26:86–91.
- Kralj A, Bajd T, Turk R. Enhancement of gait restoration in spinal injured patients by functional electrical stimulation. *Clin Orthop Relat Res*. 1988;233:34–43.
- Wieler M, Stein RB, Ladouceur M, et al. Multicenter evaluation of electrical stimulation systems for walking. *Arch Phys Med Rehabil*. 1999;80:495–500.
- Mangold S, Keller T, Curt A, et al. Transcutaneous functional electrical stimulation for grasping in subjects with cervical spinal cord injury. *Spinal Cord*. 2005;43:1–13.
- Binder-Macleod SA, Lee SCK. Assessment of efficacy of functional electrical stimulation in patients with hemiplegia. *Top Stroke Rehabil*. 1997;3:88–98.
- Burridge JH, Taylor PN, Hagan SA, et al. The effects of common peroneal stimulation on the effort and speed of walking: a randomized controlled trial with chronic hemiplegic patients. *Clin Rehabil*. 1997;11:201–210.
- Chae J, Yu DT. Neuromuscular electrical stimulation for motor restoration in hemiparesis. *Top Stroke Rehabil*. 2002;8:24–39.
- Johnson CA, Burridge JH, Strike PW, et al. The effect of combined use of botulinum toxin type A and functional electric stimulation in the treatment of spastic drop foot after stroke: a preliminary investigation. *Arch Phys Med Rehabil*. 2004;85:902–909.
- Kottink AI, Oostendorp LJ, Buurke JH, et al. The orthotic effect of functional electrical stimulation on the improvement of walking in stroke patients with a dropped foot: a systematic review. *Artif Organs*. 2004;28:577–586.
- Ring H, Rosenthal N. Controlled study of neuroprosthetic functional electrical stimulation in sub-acute post-stroke rehabilitation. *J Rehabil Med*. 2005;37:32–36.
- Taylor PN, Burridge JH, Dunkerley AL, et al. Clinical use of the Odstock dropped foot stimulator: its effect on the speed and effort of walking. *Arch Phys Med Rehabil*. 1999;80:1577–1583.
- Voigt M, Sinkjaer T. Kinematic and kinetic analysis of the walking pattern in hemiplegic patients with foot-drop using a peroneal nerve stimulator. *Clin Biomech (Bristol, Avon)*. 2000;15:340–351.
- Weber DJ, Stein RB, Chan KM, et al. BIONic WalkAide for correcting foot drop. *IEEE Trans Neural Syst Rehabil Eng*. 2005;13:242–246.
- Schmidt RA, Lee TD. *Motor Control and Learning: A Behavioral Emphasis*. Champaign, IL: Human Kinetics, Inc.; 2005.
- Schmidt RA, Wulf G. Continuous concurrent feedback degrades skill learning: implications for training and simulation. *Hum Factors*. 1997;39:509–525.
- Colarusso RP, Hammill DD. *Motor-Free Visual Perception Test (MVPT-3)*. Novato, CA: Academic Therapy Publications; 2006.

44. Folstein MF, Folstein SE, McHugh PR. "Mini-mental state." A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res.* 1975;12:189-198.
45. Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys Ther.* 1987;67:206-207.
46. Berg KO, Wood-Dauphinee SL, Williams JI, et al. Measuring balance in the elderly: validation of an instrument. *Can J Public Health.* 1992; 83(suppl 2):S7-S11.
47. Lindmark B, Hamrin E. Evaluation of functional capacity after stroke as a basis for active intervention. Presentation of a modified chart for motor capacity assessment and its reliability. *Scand J Rehabil Med.* 1988;20: 103-109.
48. Podsiadlo D, Richardson S. The timed "Up & Go": a test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc.* 1991; 39:142-148.
49. Herbert RD, Gandevia SC. Twitch interpolation in human muscles: mechanisms and implications for measurement of voluntary activation. *J Neurophysiol.* 1999;82:2271-2283.
50. Norregaard J, Lykkegaard JJ, Bulow PM, et al. The twitch interpolation technique for the estimation of true quadriceps muscle strength. *Clin Physiol (Oxford, England).* 1997;17:523-532.
51. Binder-Macleod SA, Kesar T. Catchlike property of skeletal muscle: recent findings and clinical implications. *Muscle Nerve.* 2005;31:681-693.
52. Shumway-Cook A, Brauer S, Woollacott M. Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test. *Phys Ther.* 2000;80:896-903.
53. Shumway-Cook A, Woollacott M. *Motor Control: Theory and Practical Applications.* Baltimore, MD: Williams & Wilkins; 1995.
54. Bogle Thorbahn LD, Newton RA. Use of the Berg Balance Test to predict falls in elderly persons. *Phys Ther.* 1996;76:576-583; discussion 584-585.
55. Mao HF, Hsueh IP, Tang PF, et al. Analysis and comparison of the psychometric properties of three balance measures for stroke patients. *Stroke.* 2002;33:1022-1027.
56. Chae J, Yu D. A critical review of neuromuscular electrical stimulation for treatment of motor dysfunction in hemiplegia. *Assist Technol.* 2000; 12:33-49.
57. de Kroon JR, van der Lee JH, IJzerman MJ, et al. Therapeutic electrical stimulation to improve motor control and functional abilities of the upper extremity after stroke: a systematic review. *Clin Rehabil.* 2002; 16:350-360.
58. Peckham PH, Knutson JS. Functional electrical stimulation for neuromuscular applications. *Annu Rev Biomed Eng.* 2005;7:327-360.
59. Stein RB, Chong S, Everaert DG, et al. A multicenter trial of a footdrop stimulator controlled by a tilt sensor. *Neurorehabil Neural Repair.* 2006;20:371-379.
60. Glanz M, Klawansky S, Stason W, et al. Functional electrostimulation in poststroke rehabilitation: a meta-analysis of the randomized controlled trials. *Arch Phys Med Rehabil.* 1996;77:549-553.
61. Sherwood DE, Lee TD. Schema theory: critical review and implications for the role of cognition in a new theory of motor learning. *Res Q Exerc Sport.* 2003;74:376-382.
62. Hanlon RE. Motor learning following unilateral stroke. *Arch Phys Med Rehabil.* 1996;77:811-815.
63. Winstein CJ, Merians AS, Sullivan KJ. Motor learning after unilateral brain damage. *Neuropsychologia.* 1999;37:975-987.