Concepts of Motor Learning Applied to a Rehabilitation Protocol Using Biofeedback to Improve Gait in a Chronic Stroke Patient: An A-B System Study With Multiple Gait Analyses

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Objective. The impact of electromyographic biofeedback (EMG BFB) applied during functional gait activities and employed in accord with theories on motor learning was investigated in a chronic hemiplegic patient. *Methods.* A single-subject A-B design was used. EMG BFB was applied to the triceps surae during gait. A rehabilitation program with a fading frequency of BFB application and an increasing variability in the task training was implemented. Responses to the rehabilitation program were documented via multiple quantitative gait analyses, performed during a baseline, treatment, and at follow-up 6 weeks after the end of treatment. *Results.* From baseline to end of treatment, there were significant changes in ankle power at push-off, both in amplitude and timing, as well as onset of ankle power at push-off relative to heel strike of the healthy leg. There was a significant increase in gait velocity, step length of the healthy side, stride length, and stride frequency. At follow-up, changes were still significantly different from baseline and the patient had reduced the use of the cane in activities of daily living. *Conclusions.* BFB appears to have been effective in promoting positive changes in gait in this pilot study. The rehabilitation protocol also appeared to be effective in promoting learning and the incorporation of trained activities into daily activities.

Key Words: *Gait rehabilitation—Biofeedback—Gait analysis—Motor learning—Stroke.*

Faster and more efficient gait is an important goal of rehabilitation after stroke, especially for the chronic stroke patient who often continues to be limited in daily activities by slow insecure gait. Well-defined, efficient, and effective rehabilitation protocols are needed for this population. To maximize the benefits of the training, known principles of motor learning should be applied to the treatment protocols.[1,2]

For learning a complex motor skill, it has been suggested that a fading schedule of feedback (frequent feedback early in the practice that gradually reduces toward the end) may combine the benefits of guiding learners into the right "ballpark" early in practice while gradually making them less dependent on augmented feedback later.[3,4] Variable practice is another learning paradigm that has been used to promote learning of new motor skills in healthy subjects on various motor tasks, a method that apparently allows the development and retention of effective strategies for motor control.[5] A treatment protocol based on both these practice paradigms for motor control may maximize the performance and the learning of a task such as more functional gait in a population afflicted with stroke.

The techniques of biofeedback (BFB) have already been used extensively in various areas of rehabilitation, and several studies have used BFB, focusing on improving various aspects of gait in patients with chronic stroke, with encouraging results.[6-11] In normal gait, the ankle plantar flexors produce about 80% of the total energy necessary during the gait.[12] The work of the ankle plantar flexors is primarily used to contribute to the forward motion during gait, and thus it plays a fundamental role in determining gait velocity.[10] Patients with hemiparesis tend to have a severe reduction of ankle power in the push-off phase of gait as well as a much reduced velocity in gait.[13]

The purpose of this single-subject case A-B study was to examine the efficiency of BFB training combined with theories of motor learning in improving performance and learning of gait parameters after stroke. It was expected that an increased energy production in the push-off phase of gait would be associated with changes in selected kinematic and kinetic measures, as well as

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with increased gait velocity, step length of the nonaffected side, and stride length. Moreover, it was expected that these changes would become incorporated into daily walking activities.

METHODS AND PROCEDURES

Subject

The patient was a 55-year-old man with a right hemiparesis following an ischemic lesion to the left hemisphere about 3 1/2 years prior to the study. A year after the stroke, the patient was walking independently with a cane. Gait analysis, performed without the cane at the beginning of the baseline phase, evidenced a markedly reduced power production of the ankle plantar flexors, as well as much reduced gait velocity and step frequency and a shortening of steps bilaterally. The patient made 1st ground contact with the heel and kept the knee in slight flexion throughout the gait cycle. The patient's data from clinical tests at the beginning of the baseline phase were 30.2 s at the timed walking test[14] and 26/26 and 95/100 points on the Modified Minimental Index[15] and Modified Barthel Index, respectively.

Study Design

A single-system A-B design, with follow-up 6 weeks after the end of the treatment period, was used. The patient did not receive any treatment for the 1st 2 weeks. In these 2 weeks, quantitative gait analysis (E.Li.Te, BTS, Milan) was performed in 5 sessions on different days to collect baseline data. These baseline measures were then followed by electromyographic biofeedback (EMG BFB) treatments 3 times a week for a total of 20 treatment sessions, with quantitative gait measures collected approximately 2 h after each treatment. Treatment sessions lasted about 45 min. The last gait measures were collected the day after the last treatment session. A follow-up gait assessment was carried out 6 weeks after the end of the study to assess the learning effect.

Training Procedures

A rehabilitation protocol was designed following the theorem of motor control learning.[15-17] The goal was to improve functional gait; thus, feedback was delivered during walk overground. EMG BFB was applied to the gastrocnemius lateralis. An auditory feedback tone was used to indicate whether push-off power met the target.

Treatment Phases

The therapeutic sessions were divided into 4 phases. The aims of those phases were to improve gait performance, to increase patient's auto error detection, and to transfer acquired skills during biofeedback condition to a context in which the feedback was no longer available.

In the 1st phase (1st–5th treatments), practice was kept constant, that is, BFB EMG was applied during comfortable gait of the patient. Biofeedback and verbal instructions were constantly provided. During comfortable walk overground, the patient was instructed to lift the heel and allow the knee to bend while pushing and leaving the ground.

In the 2nd phase (6th–10th treatments), a variable practice paradigm (e.g., different step lengths, variable speed) was applied with constant BFB EMG. In this phase, just summary feedback was provided.

In the 3rd phase (11th–15th treatments), variable practice (i.e., as above and variable terrain) and patient's error auto detection were used with intermittent BFB EMG.

In the 4th phase, BFB was mostly withdrawn and practice continued to be variable (as above).

Gait Analysis

Gait analysis was conducted on an 8-m walkway. The subject was recorded while walking in comfortable shoes at his own comfortable speed along the walkway. Three-dimensional kinematics of the subject's lower limbs were documented with the ELITE motion analysis system using the SAFlo protocol.[16] Ground reaction forces were measured with a Kistler force plate (Winterthur, Milan) (50 Hz). EMG recordings were made with an electromyographic 8-channel BTS (Milan) at 500 Hz.

Outcome Measures

General parameters, velocity, frequency, stride length, and step length were normalized with respect to the patient's height (h). Specific variables of outcome were decided observing the graphics of the first extraction of the various gait variables (Table 1).

Treatment Device

The biofeedback device was SATEM Mygotron (SATEM srl, Roma, Italy). EMG-rectified and 100-ms averaged data were recorded at 150 Hz, bandpass filtered at 20 to 950 Hz, and then amplified with a gain of

Table 1. Outcome Variables: Pre-, Post-, Follow-Up

Outcome Variables	Pre-	(SD)	Post-	(SD)	FU
Ankle					
Timing ankle power peak (% cycle)	48.22	(1.06)	52.33	(1.30)	50.00
Ankle power peak (W/Kg)	35.90	(3.53)	50.80	(4.75)	48.90
HS healthy-onset power (% cycle)	–5.06	(0.45)	–2.56	(0.20)	–3
Knee					
Onset knee flex pre-swing (% cycle)	35.90	(0.78)	41.57	(1.20)	39.00
Max knee flex in swing (deg)	50.59	(4.09)	51.57	(3.03)	48.81
Knee flexion at power peak (deg)	16.20	(4.57)	17.70	(3.03)	16.86
Pelvis					
Trendelemburg (deg)	–4.72	(0.67)	–4.47	(2.69)	–2.03
Hip frontal moment (N • m/Kg)	56.61	(12.56)	62.12	(4.54)	47.73
Pelvis rotation TO-HS (deg)	1.01	(2.32)	2.62	(1.51)	2.55
General					
Mean velocity (%h/s)	27.19	(0.91)	37.39	(1.64)	38.03
Stride length (%h)	49.64	(1.95)	62.80	(0.68)	63.20
Healthy side stride length (%h)	23.41	(0.41)	28.06	(0.25)	27.08
Stride frequency (stride/s)	0.54	(0.01)	0.59	(0.02)	0.58

Ankle, knee, pelvis, and general variables at pre-treatment, post-treatment and follow-up (FU). The pre- values are the mean and (SD) of the 5 baseline assessments. The post- values are the mean and (SD) of the last 3 assessments of the treatment phase.

40,000 (50 μVrms range). EMG was recorded and presented as an analogical audio signal to the patient.

Data Analysis

A series of data points were collected before intervention, serving to establish a baseline, which was then followed by a series of data points collected during intervention and at follow-up. Each data point was computed as the mean of 5 walks performed during each session in the gait lab. The 2 standard deviation band method[17] was used to analyze the data for changes. This method assesses variability in the baseline phase calculating the mean and standard deviation in that phase. If at least 2 consecutive points in the intervention phase fall outside the band, the change from baseline to intervention phase is considered significant.

RESULTS

Ankle (Figure 1, Table 1): Analysis of graphed data points revealed significant changes in ankle plantar power peak (Figure 1, graph A) from baseline to treatment sessions. The mean improvement between baseline measurements and the end of the treatment phase was 42%. At follow-up 6 weeks later, ankle power peak was still significantly higher than baseline. High variability was observed during the 1st 2 blocks of treatment sessions, a variability that then decreased toward the end of the treatment.

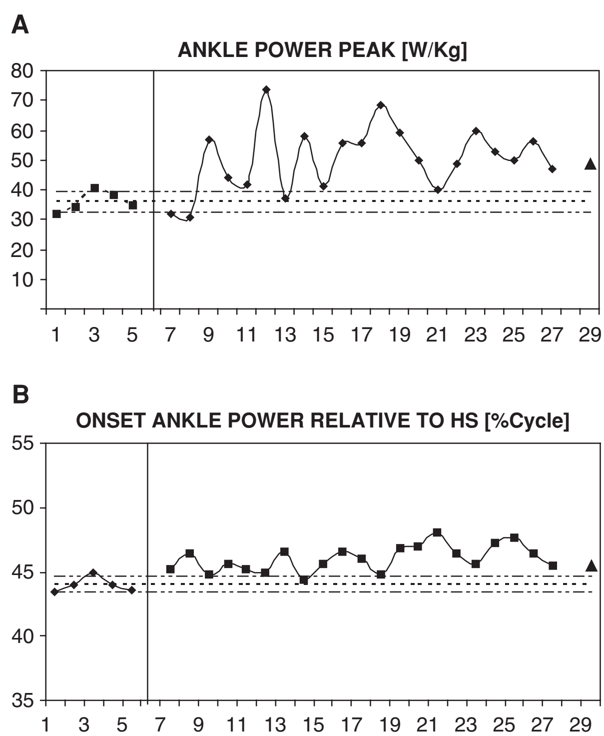

Figure 1. Ankle power peak (A) and onset of ankle power with respect to heel strike (HS) (B).

Onset of ankle power relative to heel strike (HS) of the healthy leg was significantly anticipated following treatment, which indicates that the patient was able to begin effective push-off earlier (Figure 1, graph B). At baseline,

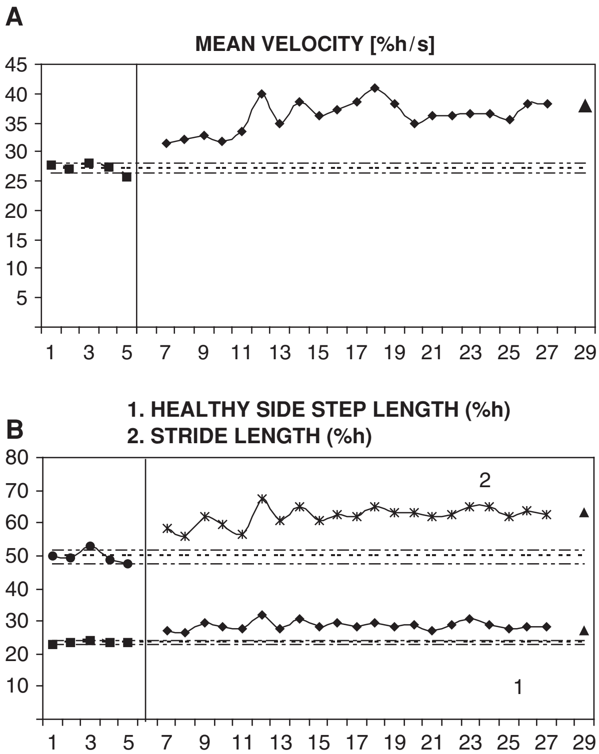

Figure 2. Mean velocity (A), healthy side step length and stride length (B). The vertical lines divide the baseline and treatment phases. The dotted horizontal line represents the mean values of baseline; the other two horizontal lines represent the two standard deviation bands of baseline data points. The follow-up is represented by a filled triangle.

push-off of the affected leg was begun when the mid-foot of the nonaffected leg was already down, whereas following treatment, push-off began near heel touch of the nonaffected leg. This anticipation persisted at follow-up.

Knee (Table 1): Visual analysis revealed no significant changes in maximum flexion of the knee during swing or in knee flexion at power peak.

Pelvis (Table 1): Visual analysis of pelvic and hip movements during gait revealed no significant changes from baseline to treatment phase.

General parameters (Figure 2): Visual analysis of velocity revealed an immediate significant improvement in velocity following the 1st treatment sessions (graph A). At the 2nd treatment phase, there was increased variability with somewhat higher velocity that then stabilized and remained fairly constant for the last 2 phases of treatment. Thus, there was an increase in velocity from baseline to end of treatment of about 27%, which persisted at follow-up. Similarly there were significant increases in step length of the nonaffected leg (graph B-1) and in stride length (graph B-2) already after the 1st treatment sessions that then remained significantly higher throughout the treatment sessions, with further increases in stride length from the 6th session. At follow-up, those changes remained significant. Stride frequency (Table 1) changed from baseline to end of treatment and remained significantly higher at follow-up (0.54 steps/s to 0.58 steps/s).

DISCUSSION

Our data indicate that for this subject, the BFB was effective in increasing the power production of the ankle plantar flexors. The increase in power peak at push-off was coupled with an important increase in velocity of gait, as well as an increase in stride length and frequency. Our findings concur with the findings of Colborne and colleagues[6] that found an increase in push-off impulse concurrent with changes in velocity and in stride length. For our subject, the timing of the onset of the push-off power was delayed with treatment, whereas the peak power was anticipated relative to the HS of the nonaffected leg, indicating that a larger part of the power produced by the plantar flexors may have been effective for forward propulsion, resulting in a faster gait and longer stride length. Performance during the 1st 10 treatment sessions tended to be very variable, whereas toward the latter part of the treatment period, it remained more stable.

Although the BFB treatment was specifically aimed toward increasing push-off power, the change in step length on the affected side, a symmetry parameter, indicates a more general benefit of the BFB treatment and of the treatment protocol. This may be due to an overall improvement in balance and strength. The patient at the end of treatment used the cane only for longer walks and for security when he was in crowded places. The changes we saw in measured variables were thus concurrent with changes in functional activities of daily living.

Continuous feedback and blocking, that is, constant feedback applied only during normal walking in the beginning, may have enhanced fundamental spatial-temporal patterning. The feedback during varying environmental conditions (different speeds, size of steps, etc.) later in treatment may have trained processes responsible for scaling the action properly to meet various environmental demands.[3,4]

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