

Special Article – Gait Rehabilitation

Changes in Post-Stroke Gait Biomechanics Induced by One Session of Gait Training

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The objective of this study was to determine whether one session of targeted locomotor training can induce measurable improvements in the post-stroke gait impairments. Thirteen individuals with chronic post-stroke hemiparesis participated in one locomotor training session combining fast treadmill training and functional electrical stimulation (FES) of ankle dorsi- and plantar-flexor muscles. Three dimensional gait analysis was performed to assess within-session changes (after versus before training) in gait biomechanics at the subject's self-selected speed without FES. Our results showed that one session of locomotor training resulted in significant improvements in peak anterior ground reaction force (AGRF) and AGRF integral for the paretic leg. Additionally, individual subject data showed that a majority of study participants demonstrated improvements in the primary outcome variables following the training session. This study demonstrates, for the first time, that a single session of intense, targeted post-stroke locomotor retraining can induce significant improvements in post-stroke gait biomechanics. We posit that the within-session changes induced by a single exposure to gait training can be used to predict whether an individual is responsive to a particular gait intervention, and aid with the development of individualized gait retraining strategies. Future studies are needed to determine whether these single-session improvements in biomechanics are accompanied by short-term changes in corticospinal excitability, and whether single-session responses can serve as predictors for the longer-term effects of the intervention with other targeted gait interventions.

Keywords: Gait rehabilitation; Stroke; Biomechanics; Propulsion; Functional electrical stimulation

Abbreviations

FES: Functional Electrical Stimulation; AGRF: Anterior Ground Reaction Force; SS Speed: Self-Selected Speed

Introduction

Common impairments in post-stroke gait kinematics include reduced hip, knee, and ankle flexion during swing phase. To alleviate reduced dorsiflexion during swing phase or 'foot drop', functional electrical stimulation (FES) delivered to ankle dorsi-flexor muscles is commonly used as an intervention [1-3]. Previous studies from our laboratory have shown that in contrast to the traditional FES approach of stimulating the ankle dorsiflexors during swing phase, delivering FES to both dorsi- and plantar-flexor muscles provides greater biomechanical advantages and may address both swing phase and stance phase gait deficits post-stroke [4,5]. Decreased push-off force generation by the paretic limb during terminal stance is a post-stroke impairment that has recently received attention in the literature due to its relationships with hemiparetic severity and walking speed [6,7]. 'FastFES', a novel gait rehabilitation intervention involving the combination of fast treadmill training with functional electrical stimulation of ankle plantar-and dorsi-flexor muscles, is a novel and effective post-stroke locomotor training intervention [5,8-10]. The FastFES intervention targets slowed walking speed, decreased paretic push-off and decreased knee and ankle flexion during swing. Twelve

weeks (36 sessions) of FastFES gait training have been shown to produce significant improvements in walking function, activity, and participation post-stroke [8,9,10,11].

While improvements in post-stroke gait are commonly observed after several weeks of training with FastFES and other gait retraining interventions, when and how these improvements in gait first evolve is unclear. Experiments employing a single session of exposure to unique, challenging, and well-controlled locomotor paradigm, such as walking with a weight added to one leg [12], stepping on a rotating disc [13], and split-belt treadmill walking [14] demonstrate that human locomotion adapts rapidly in the short-term. However, long-lasting therapeutic effects of these locomotor adaptation paradigms have not been well studied. In contrast, FastFES has been shown to produce marked long-term therapeutic benefits on post-stroke gait, but it is not known whether it can induce measurable improvements in post-stroke gait impairments within a single session.

The changes induced in gait following each session of gait training may be important because they form the 'building blocks' that accumulate to produce the long-term therapeutic effects of an intervention. We posit that within-session changes in gait performance, if present, may provide a valuable 'probe' or evaluation tool to assess an individual's short-term responsiveness to an intervention and aid with future development of customized gait retraining strategies. For example, if a single session of training is

Table 1: Subject demographics and clinical characteristics.

Subject	Gender	Age (years)	Side of paresis	Stroke Onset (months)	SS Gait Speed (m/s)	Fast (Training) Speed (m/s)	Fugl-Meyer LE Score	TUG Time (s)	6-min walk distance (meters)
1	M	70.5	L	44.0	0.9	0.95-1.05	21	15.7	242.7
2	M	75	R	87.0	0.5	0.66-0.76	14	18.8	262.8
8	M	60	L	32.0	0.38	0.42	12	30.3	146.6
3	M	47	R	15.5	0.4	0.93-1.05	15	27.1	177.9
4	F	71	L	15.9	0.3	0.6-0.73	22	35.1	116.0
5	F	60.5	R	10.3	0.32	0.36-0.49	11	28.9	108.1
6	M	68	L	35.6	0.79	1.01	31	10.1	316.3
7	M	68	L	11.0	0.65	0.65	21	17.0	316.3
10	M	57.5	L	6.6	0.87	0.5-0.61	28	11.4	322.5
11	M	63.5	R	90.3	0.92	1.02-1.05	23	9.6	424.9
9	M	54.5	L	5.8	1.03	1.19	27	10.9	335.1
12	M	42	L	9.5	0.94	0.87	22	12.0	395.6
13	M	60	R	14.5	0.83	1.0-1.05	18	15.7	370.6
Mean		61.3		29.1	0.7	0.8	20.4	18.7	284.9
Stdev		9.6		29.0	0.3	0.3	6.2	8.7	99.6

found to induce changes in gait biomechanics, before implementing a long-term gait rehabilitation program comprising 18 to 24 sessions over the course of 6 to 12 weeks, perhaps biomechanical data obtained during a single session of training can be utilized to determine whether the individual shows any measurable improvements in gait biomechanics following a single session of training. Furthermore, establishing that within-session changes in gait biomechanics are induced by clinical training protocols such as FastFES would lay foundations for future studies investigating the neurophysiological and biomechanical mechanisms underlying the effects of gait rehabilitation. The objective of this study, therefore, was to determine whether one FastFES gait training session (comprising 30-minutes of stepping practice with and without FES) can induce improvements in post-stroke gait biomechanics, as demonstrated by carry-over of improvements in gait during walking without FES.

Materials and Methods

Subjects

Thirteen individuals with chronic post-stroke hemiparesis (age 42-75 years, 2 females, and time post-stroke 5-90 months) were recruited for the study (Table 1). Study inclusion criteria included >6 months post-stroke and the ability to walk for 4-minutes without an orthosis. Individuals were excluded if they had neurological diseases

other than stroke, neglect, hemianopia, orthopedic problems affecting walking, or inability to communicate with investigators. Participants provided informed consent and study procedures were approved by the institutional review board.

After completion of initial screening and informed consent, subjects participated in a clinical testing session comprising measurement of: (i) over ground self-selected walking speed using the 6-meter walk test (SS speed used for pre-test and post-test measurements during each session), (ii) overground endurance using the 6-minute walk test, (iii) fastest speed subjects could maintain on a treadmill for 4-minutes (Fast speed used during gait training), (iv) lower extremity portion of the Fugl-Meyer, and (v) the timed up and go test. Following completion of clinical testing, all participants completed one FastFES training session. Three dimensional gait analyses were performed to measure gait biomechanics before (Pre-test) and after (Post-test) the gait training session (Figure 1). These tests were performed during walking without FES and at the same speed (each participant's self-selected gait speed determined at the start of the training session).

Methods for gait analysis

An 8-camera motion analysis system (Motion Analysis, Santa Rosa, CA) was used to measure positions of retro-reflective markers

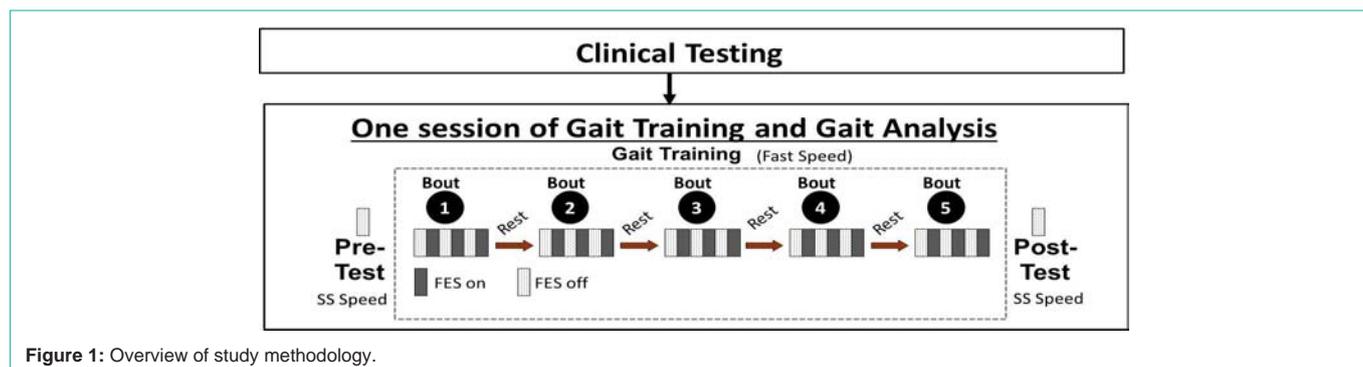


Figure 1: Overview of study methodology.

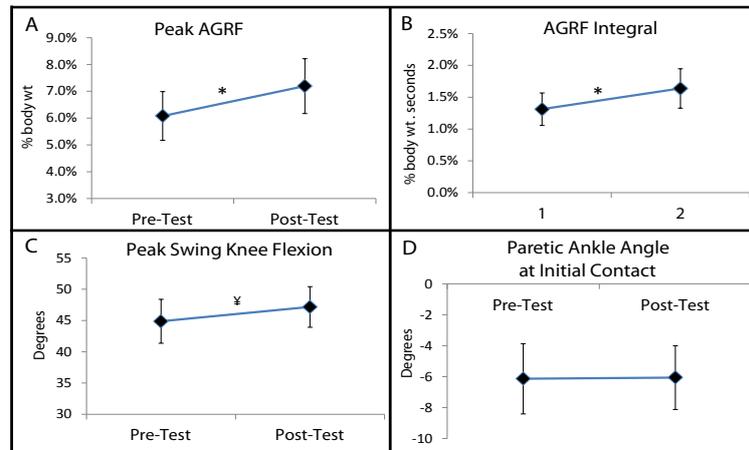


Figure 2: Group means and standard errors for peak AGRF (N=13), paretic AGRF integral (N=13), swing phase peak knee flexion (N=13, positive values indicate knee flexion), and ankle angle at initial contact (N=13, positive values indicate dorsiflexion) obtained before (pre-test) and after (post-test) after one session of FastFES gait training. The individual subject data corresponding to these group means are shown in Figure 3. *Significant effect of time (post-test versus pre-test) ($p < 0.05$). ‡ Trend for statistical significance ($p = 0.1$).

attached to the pelvis and bilateral thigh, shank, and foot segments [15]. Participants walked on a split-belt treadmill instrumented with force platforms embedded within each belt (Bertec, Columbus, OH). Marker and ground reaction force (GRF) data were sampled at 100- and 1000-Hz respectively. During gait analysis, participants walked without FES or an orthoses. An overhead harness without bodyweight support provided safety.

Methods for locomotor training

The FastFES training comprised a total of 30 minutes of walking practice (five 6-minute bouts with seated rest breaks between bouts), as described previously [4,16] (See Figure 1 for additional details). Each 6-minute bout comprised treadmill walking at the fastest speed participants could maintain with alternating 1-minute periods of walking with and without FES (Figure 1). The fast training speed was determined at the start of the session and if the subjects were able, the fast training speed was progressed during the training session as well (i.e. training speed may be increased from the 1st to the 5th training bout). During walking with FES, FES was delivered via surface electrodes to ankle dorsi-flexor muscles during paretic swing phase and to ankle plantar-flexor muscles during paretic terminal stance phase, as described previously [4,9,16].

Dependent variables and statistical analyses

Gait events were determined using a 20-Newton vertical GRF force threshold. GRF data were normalized to body weight. The gait phase between the point where the antero-posterior GRF crossed zero (i.e. transitioned from posterior to anterior) and the end of stance phase was identified as the portion of the gait cycle when participants demonstrated anteriorly-directed GRFs. The peak paretic anterior GRF (peak AGRF) and paretic AGRF integral (i.e., area under the AGRF curve) were the primary dependent variables measuring paretic propulsion. Secondary outcome variables included peak knee flexion angle during swing phase and ankle dorsi/plantar-flexion angle at initial contact. These 4 variables were selected to assess the specific impairments targeted by the intervention.

For each dependent variable, a paired t-test was performed to determine if there was a difference in the dependent variable at pre-

test versus post-test. Improvements in gait biomechanics induced by the single session of gait training would be present if the comparisons demonstrated greater peak AGRF, greater AGRF integral, greater peak swing phase knee flexion angle, and reduced foot-drop (ankle angles closer to 0° plantar/dorsi-flexion) at Post-test versus Pre-test. The Kolmogorov-Smirnov Test was used to confirm that the data were normally distributed.

Results

Complete data were obtained on all 13 subjects (Table 1) for peak AGRF, paretic AGRF integral, and ankle angle at initial contact. Data from the first exposure to FastFES gait training session were utilized for the current study. However, for one participant, due to gaps and issues with marker data obtained during from the first training session, data from a second training session were included in the analysis.

The paired t-tests revealed significantly greater values of peak AGRF ($p = 0.014$) and AGRF integral ($p = 0.004$) during the post-test versus the pre-test (Figure 2). The mean difference between Post-test and Pre-test (mean difference \pm standard error of difference) was $1.11 \pm 0.39\%$ body weight for peak AGRF and $0.33 \pm 0.08\%$ body weight.seconds for AGRF integral. The paired t-test for peak swing phase knee flexion was not significant but showed a trend ($p = 0.12$) for greater values at post-test versus pre-test (Figure 2; mean difference between Post- and Pre-test = $2.3 \pm 1.4^\circ$). The paired t-test detected no significant difference between pre- and post-test values for ankle angle at initial contact ($p = 0.95$; mean difference between Post- and Pre-test = $0.07 \pm 1.3^\circ$) (Figure 2). Additionally, analysis of the values of the 4 dependent variables at Pre- and Post-test for individual subject data corresponding to these group statistics showed that for the primary outcome variables, i.e. peak AGRF and AGRF integral, a majority of the subjects (11 of 13) showed improvements following the training session (depicted by bold lines in Figure 3). For the secondary outcome variable of ankle angle at initial contact, there was greater inter-individual variability in the magnitude of within-session changes, and while a majority of subjects still showed within-session improvements (shown by bold lines in Figure 3), 5 of the participants

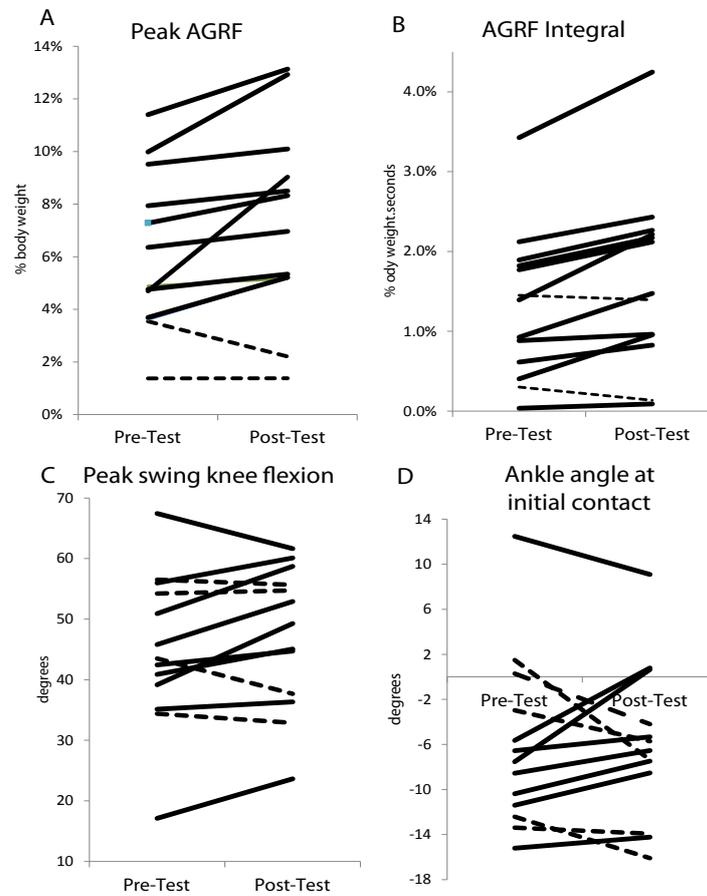


Figure 3: Individual subject data (corresponding to the averaged or group data shown in Figure 2) showing (A) peak AGRF, (B) paretic AGRF integral, (C) swing phase peak knee flexion, and (D) ankle angle at initial contact (positive values indicate dorsiflexion) obtained before (pre-test) and after (post-test) after one session of FastFES gait training. The study subjects who showed an increase (or improvement) in the gait variable are depicted with bold lines, and subjects who showed no change or decrement (worsening) of the gait variable are depicted with the shaded lines. These graphs demonstrate the inter-subject variability in the single-session responses to gait training, and also show that for the primary gait deficit targeted during training (paretic propulsion (A and B)), a majority of subjects showed improvements following the training session.

showed no change or a worsening of the variables following training (shown by shaded lines in Figure 3).

Discussion

This study demonstrates, for the first time, that a single session of intense gait training targeting paretic push-off force generation, an important post-stroke gait impairment shown to be associated with hemiparetic severity and over ground gait speed, can induce significant improvements in push-off of the paretic leg of individuals post-stroke. Significantly greater push-off forces (paretic peak AGRF and AGRF integral), and a trend for greater swing phase knee flexion angles, were demonstrated by the paretic limb after the FastFES gait training session, indicating that FastFES training may be sufficiently intensive and robust to induce positive effects on gait impairments within one session. It is important to note that although previous studies have shown improvements in gait biomechanics and walking function after several weeks of FastFES gait training [8,9,11], or immediate improvements in gait biomechanics during short bouts of walking with versus without FES [4,16], improvements in gait deficits (measured during walking without FES) following a single training session have not been previously documented in the literature.

During FastFES, the combination of fast treadmill training with plantar-flexor FES is designed to train stroke survivors to generate greater push-off forces with their paretic ankle muscles [4,5]. The within-session improvements in push-off forces observed in our study suggest that the FastFES training strategy successfully modulated push-off force generation after a single session. Some what consistent with previous biomechanical simulations [17] and experimental studies [4] suggesting that push-off force generation contributes to swing phase knee flexion, in the current study, a trend for improvements in knee flexion were observed after the training session. In addition, the consistency of the *direction* of the within-session change in paretic push-off forces and knee flexion across subjects suggests that these within-session improvements were robust (see individual subject data in Figure 3). The lack of within-session change in ankle kinematics may be attributed to dorsi-flexor muscle fatigue, and is an interesting finding that merits further investigation, especially because foot drop is an important and prevalent post-stroke impairment [1]. Furthermore, it is important to note that these within-session changes were observed as subjects walked at a speed (self-selected speed) different from the speed they trained at (fast speed), and during walking without FES, suggesting short-

term carry-over or retention of modified gait biomechanics patterns learned during training.

In the current study, unlike previous studies reporting the immediate or long-term (over many weeks) therapeutic effects of the gait training, we focused on changes in gait induced after a single session of gait training. However, the study is limited by a small sample size comprising a majority of male stroke survivors. Additionally, although we demonstrate that a single training session induces improvements in post-stroke biomechanical impairments targeted during training, the longevity or retention of these single-session changes was not evaluated, and would be an interesting focus of future investigations.

To our knowledge, no previous study has shown that improvements in post-stroke gait biomechanics can occur after a single session of *clinical* gait rehabilitation. We posit that within-session biomechanical changes, such as those demonstrated here during a single session of FastFES gait training, can be used as a quick, cost-effective probe or test to assess whether an individual is responsive to a particular treatment paradigm. Future studies are needed to determine whether other gait training interventions produce similar within-session improvements, to investigate the neural correlates underlying these within-session improvements in gait impairments, to develop strategies to maximize the magnitude of these within-session improvements, and to determine whether single-session responses to a rehabilitation treatment can serve as predictors of longer-term effects of the intervention.

Conclusion

This study demonstrated that changes in post-stroke gait biomechanics may occur following a single gait rehabilitation treatment session. Our results showed that a single session of intense, post-stroke locomotor training (FastFES) that targets paretic propulsion induced improvements in paretic push-off (peak AGRF and AGRF integral). Additionally, we demonstrated that within-session responses to gait training may vary across subjects and across different gait deficits (e.g. primary variable of peak AGRF and AGRF integral in our current study versus secondary variables of peak swing phase knee angle and ankle angle at initial contact). We postulate that an in-depth understanding of such within- and across-session time courses of change during gait retraining can help to maximize the effects of each session and each week of rehabilitation. Our findings provide support for the need for studying the effects of a single treatment session on gait as a 'probe' or 'test' for an individual's response to a rehabilitation intervention [18].

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