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Effects of Fast Functional Electrical Stimulation Gait Training on Mechanical Recovery in Post-Stroke Gait

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Abstract

Stroke leads to gait impairments that can negatively influence quality of life. Functional electrical stimulation (FES) applied during fast walking is an effective gait rehabilitation strategy that can lead to improvements in gait performance, walking speed and endurance, balance, activity, and participation post-stroke. The effect of FastFES gait training on mechanical energy utilization is not well understood. The objective of this study was to test the effects of 12-weeks of FastFES gait training on mechanical recovery indices of post-stroke gait. Kinematic data were collected from 11 stroke survivors before and after 12-weeks of FastFES training. Mechanical recovery was calculated from the positive changes in vertical, anterior-posterior, and medial-lateral components of COM energy. The average mechanical recovery increased from 34.5% before training to 40.0% after training. The increase was statistically significant (p=.014). The average self-selected walking speed increased from 0.4m/s to 0.7m/s after the 12-week FastFES training. The results indicate that the subjects were better able to generate and utilize the external mechanical energy of walking after FastFES gait training. FastFES gait training has the capacity to increase the gait speed, improve the mechanical recovery, and reduce the mechanical energy expenditure of stroke survivors when they walk.

Keywords

Functional electrical stimulation; stroke; gait; mechanical recovery; training

Introduction

Stroke leads to gait impairments such as slowed walking speeds, inter-limb asymmetry, and increased energy consumption [1]. Functional electrical stimulation (FES) applied to the dorsiflexor muscles of stroke survivors is commonly used to address foot-drop, [2] and therefore improve safety, speed, and efficiency of walking [3]. However, FES of the dorsiflexors alone does not address other critical gait deficits such as reduced ankle plantar flexor moment and push-off forces during terminal stance and decreased knee flexion angle during swing. Recent work has shown that delivering FES to multiple muscles during gait, especially to ankle plantarflexors, produces greater immediate improvements in gait compared to the traditional approach of delivering dorsiflexor FES alone [2].

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Treadmill training has also recently emerged as an effective gait rehabilitation intervention [4]. Treadmill training at fast speeds can provide several advantages, such as improved cadence and gait symmetry [5]. We developed and tested a novel gait rehabilitation intervention combining functional electrical stimulation (FES) of ankle dorsiflexor and plantar flexor muscles and Fast treadmill walking (FastFES). We hypothesized that combining these 2 independent interventions would enable us to correct multiple post-stroke gait impairments (decreased forward propulsion, decreased swing phase knee flexion, decreased trailing limb angle, and footdrop), and thereby produce maximal improvements in walking speed and endurance. The preliminary results from the 12-week FastFES gait study show improvements in gait performance, walking speed and endurance, balance, activity, and participation post-stroke.

The mechanical recovery index (R) is a measure of the mechanical energy exchange that is preserved through the pendulum-like motion of the whole-body center of mass (COM) during gait [6]. It can provide insights into the effects of FastFES training on post-stroke gait mechanics and energetics, and therefore, help us to understand the mechanisms underlying the FastFES intervention. The objective of this study, therefore, was to test the effects of 12-weeks of FastFES gait training on mechanical recovery indices of post-stroke gait.

Material and Methods

Subjects

Eleven chronic stroke subjects (6 male; mean age 64±8yrs; mean months post-stroke 50±40mth,; mean Fugl-Meyer (LE) Score 17±3) participated in this study. All subjects received medical clearance from their physicians to participate in gait training and gave informed consent to participate in the study which was approved by the University of Delaware Human Subjects Review Board. All subjects could walk 5 minutes continuously at their self-selected speed and were not undergoing any other training.

Training

Each subject participated in 12-weeks (3 sessions/week) of gait training. Training sessions comprised five 6-minute bouts of walking with ~5-minute rest breaks between bouts (~30-minutes of fast walking each session). Training sessions comprised walking practice with and without FastFES, and also included overground walking. Training speeds were based on participant’s maximal walking speed, and progressed every 4 weeks.

FastFES During Training

During training, FastFES was delivered using surface electrical stimulation electrodes to the dorsiflexor and plantarflexor muscles. A Grass S8800 stimulator and SIU8TB stimulus isolation unit (Grass Instrument Co, Quincy, MA) delivered the stimulation (30-Hz trains, pulse duration of 300μs, 300ms long). Electrical stimulation timing was controlled using a custom-built real-time controller using input from two compression-controlled footswitches attached to the sole of the forefoot and hindfoot of the subjects’ shoes. Dorsiflexor (DF) stimulation was applied from when the forefoot switch left the ground until the hindfoot switch contacted the ground (paretic swing phase). Plantar flexor (PF) stimulation was applied from when the hindfoot switch left the ground until the forefoot switch left the ground (paretic terminal stance) [2,7].

Gait Analysis

Data were collected before and after 12-weeks of training. An 8-camera motion analysis system (Vicon 5.2, Oxford, England) recorded (100 Hz) the positions of 41 retroreflective markers placed on the bony landmarks of the foot, shank, thigh, pelvis, and trunk of the

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subjects as they walked on an instrumented treadmill (AMTI, Watertown, MA) at their self-selected speed. Body segment masses were determined from anthropometric data [8] and COM positions were calculated from marker position data using Visual 3D (C-Motion, Rockville, MD). COM positions were low-pass filtered at 6Hz. Segment velocities and accelerations were calculated by taking derivatives of the limb COM positions relative to the whole-body COM and used to calculate segment kinetic and potential energies [6].

Mechanical Recovery

Mechanical recovery was calculated to assess the energy exchange between the vertical, anterior-posterior and medial-lateral directions of the whole-body COM during gait [6,9]. Mechanical recovery (R) was calculated as:

$$R=\frac{W_v+W_{ap}+W_{ml}-W_{ext}}{W_v+W_{ap}+W_{ml}}*100\%$$

where W_v, W_{ap}, and W_{ml} are the vertical, anterior-posterior, and medial-lateral components of the whole body external work, W_{ext}, respectively. W_v, W_{ap}, and W_{ml} were calculated by summing the positive changes in vertical, anterior-posterior, and medial-lateral components of energy, respectively, averaged over eight consecutive gait cycles. To account for inter-trial and inter-subject differences, the whole body external work measures were normalized to subject body mass (kg) and distance walked (m).

Data Analysis

The Wilcoxon signed-rank test was performed to identify differences between pre-training and post-training average mechanical recovery. Significance was set at $p<0.05$.

Results

The average mechanical recovery across subjects prior to FastFES training was 34.5% (range 18.4 to 52.9%). After the 12-week FastFES training, the average mechanical recovery across subjects was 40.0% (range 30.0 to 58.8%). Mechanical recovery increased as a result of FastFES training in all but one subject (Fig. 1). The mechanical recovery levels after FastFES training were significantly higher than the pre-training levels ($p = 0.013$). Overall mechanical recovery was low relative to healthy adults walking at self-selected or slow speeds [6]. Self-selected walking speeds increased for all subjects following FastFES training. The average self-selected walking speed prior to training was 0.4m/s (range 0.3 to 0.7m/s) and after the training period was 0.7m/s (range 0.4 to 1.0m/s) (Fig. 2).

Discussion

One important finding of this study was that FastFES gait training resulted in a significant increase in mechanical recovery. Another finding was that self-selected walking speed increased after 12 weeks of FastFES gait training. Both of these outcomes provide functional benefits for stroke survivors.

It is known that an increase in the walking speed of slow walking stroke survivors is one method to improve mechanical recovery [9]. The change in self-selected walking speed had a confounding effect on the results. The mechanical energy of the COM is directly related to the kinetic energy, and thereby speed, in the anterior-posterior direction, i.e. $\frac{1}{2}mv^2$. Additionally, mechanical recovery exhibits a parabolic relationship with walking speed [6]. Therefore, with increasing speed, some post-stroke individuals may better utilize the

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mechanical energy exchanges associated with the pendulum-like motion of the body COM. Because we evaluated the subjects at their present self-selected walking speeds, which improved with the training, and not at a common forced speed, which could have negatively influenced gait performance [10,11], we cannot determine if the observed improvements would have occurred independent of changes in each subject's walking speeds. However, because increased mechanical recovery and walking speed are meaningful benefits for stroke survivors, we believe this study and its results are meritorious.

The result that mechanical recovery and speed improved after FastFES training indicates that the subjects were better able to generate and utilize the external mechanical energy of walking. This finding implies that the training improved the subjects' ability use the plantarflexors to accelerate the COM vertically up and forward over the base of support. Improved utilization of the plantarflexors in late stance would lead to higher gait speeds, which are associated with increased energy efficiency [11] and mechanical recovery [9] in post-stroke gait.

The observed increased in gait mechanical recovery and speed support the possibility that FastFES training may prolong the beneficial immediate effects of FastFES applied to the dorsiflexor and plantarflexor muscles, i.e. greater swing-phase knee flexion, greater ankle plantarflexion angle at toe-off, and greater forward propulsion [2]. In turn, prolonged training with FastFES may enable the subjects to learn to adjust their muscle activity patterns so as to gain further improvements in mechanical efficiency.

Conclusions

This study demonstrated that FastFES training has the capacity to increase the gait speed and improve the mechanical recovery of stroke survivors when they walk.

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References

1. Zamparo P, Francescato MP, Luca G, Lovati L, Prampera PE. The energy cost of level walking in patients with hemiplegia. Scand J Med Sci Sports. 1995; 5:348–352. [PubMed: 8775719]
2. Kesar TM, Perumal R, Reisman DS, Jancosko A, Rudolph KS, Higginson JS, et al. Functional electrical stimulation of ankle plantarflexor and dorsiflexor muscles: Effects on poststroke gait. Stroke. 2009; 40:3821–3827. [PubMed: 19834018]
3. Taylor PN, Burridge JH, Dunkerley AL, Wood DE, Norton JA, Singleton C, 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. [PubMed: 10597809]
4. Dickstein R. Rehabilitation of Gait Speed After Stroke: A Critical Review of Intervention Approaches. Neurorehabil Neural Repair. 2008; 22:649–660. [PubMed: 18971380]
5. Pohl M, Mehrholz J, Ritschel C, Ruckriem S. Speed-Dependent Treadmill Training in Ambulatory Hemiparetic Stroke Patients: A Randomized Controlled Trial. Stroke. 2002; 33:553–558. [PubMed: 11823669]
6. Cavagna GA, Thys H, Zamboni A. The sources of external work in level walking and running. J Physio. 1976; 262:639–657.
7. Kesar TM, Perumal R, Jancosko A, Reisman DS, Rudolph KS, Higginson JS, et al. Novel Patterns of Functional Electrical Stimulation Have an Immediate Effect on Dorsiflexor Muscle Function During Gait for People Poststroke. Phys Therapy. 2010; 90:55–66.

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8. Winter, DA. Biomechanics and Motor Control of Human Movement. 4th ed. Hoboken: Wiley; 2009.
9. Detrembleur C, Dierick F, Stoquart G, Chantraine F, Lejeune T. Energy cost, mechanical work, and efficiency of hemiparetic walking. Gait Posture. 2003; 18:47–55. [PubMed: 14654207]
10. Ralston H. Energy-speed relation and optimal speed during level walking. Int Z Angew Physiol. 1958; 17:277–283. [PubMed: 13610523]
11. Reisman DS, Rudolph KS, Farquhar WB. Influence of Speed on Walking Economy Poststroke. Neurorehabil Neural Repair. 2009; 23:529–534. [PubMed: 19126838]

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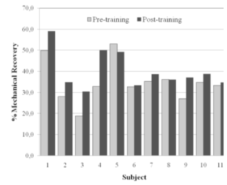

Fig. 1.
Mechanical recovery over eight gait cycles for each of the subjects as they walked prior to and after 12 weeks of FastFES training.

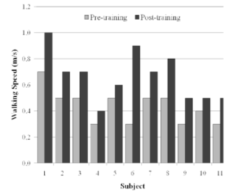

Fig. 2.
Subject pre-training (light bars) and post-training (dark bars) self-selected walking speeds.

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