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Changes in Metabolic Cost of Transport Following Locomotor Training Post-Stroke

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Abstract

Background—The energy cost of transport is higher in those with stroke compared to neurologically intact subjects and this has a negative impact on ambulatory activity and function. Whether the high energy cost of walking after stroke is influenced by gait training interventions is generally not considered.

Objective—To examine changes in the energy cost of transport with a gait training intervention after stroke and to identify whether energy cost changes independent of changes in walking speed.

Methods—Persons with chronic (>6 months) stroke participated in an intervention combining fast walking and functional electrical stimulation of the ankle dorsi- and plantar-flexor muscles. Oxygen consumption, walking speed and endurance were measured pre- and post-training. Energy and caloric cost of transport were calculated at self-selected and absolute speeds at each time point.

Results—Eleven subjects (age =61.8±8) participated. Self-selected and fastest walking speed and 6 minute walk test distance improved after the intervention (F=67.5, p<0.001; F=40.9, p<0.001; F=20.2, p=0.001). Energy and caloric cost of transport at self-selected speed improved (F=8.63, p=0.015; F=7.87, p=0.019), but did not change at an absolute speed pre- to post-intervention.

Conclusions—Energy and caloric cost of transport at self-selected walking speeds improved pre- to post-training, but were unaffected at an absolute walking speed. This suggests that the improved energy cost of transport was through improvements in the subject's self-selected walking speed. These results illustrate that improvements in walking speed following an intervention are an important mechanism by which the energy cost of transport can be reduced post-stroke.

Keywords

Locomotion; Oxygen consumption; Stroke

INTRODUCTION

It is well understood that persons with chronic stroke often have marked gait deficits resulting from their stroke¹⁻⁴. In addition, they demonstrate an increased energy cost of transport during walking^{2, 5} and cardiovascular fitness that is often well below the level needed to support activities of daily living⁶. Ganley et al. (2008) report that the energy cost of transport was 40–50% higher in persons with stroke compared to neurologically intact subjects⁵. Given the potential negative impact of increased energy cost of transport on ambulatory activity and function, it is surprising that very few locomotor training intervention studies in persons with stroke have examined the effect of training on this measure⁷.

The self-selected gait speed of those with chronic stroke is much slower⁸ than the gait speed range of 1.1–1.4 m/s that is associated with minimal energy cost of walking⁹ and is the self-selected speed range generally selected by able-bodied adults¹⁰. This narrow range indicates that able-bodied individuals typically select a gait speed that minimizes the energy cost of transport during walking⁹. The preferred gait speed range represents the nadir of a U-shaped relationship between gait speed and energy cost of transport^{9, 11-13}. Deviations to the left or right of this gait speed range are therefore associated with an increased energy cost of transport^{9, 11}.

In a recent examination of the effect of walking speed on the energy cost of transport in persons post-stroke, Reisman et al. found that the energy cost of walking decreases (i.e. walking economy improves) as speed increases above subjects' initial self-selected speed¹⁴. In this study, subjects in the “slow” group (walking speeds lower than 1.2m/s) improved their energy cost of transport when they were asked to walk at faster speeds, while those in the “fast” (walking speeds greater than 1.2 m/s) group did not¹⁴. These results reinforce the idea that walking at speeds outside of a normal walking speed range⁹ (e.g. 1.1–1.4 m/s) results in an increased energy cost of transport, even in persons post-stroke. These results also suggest that the energy cost of transport may improve following a post-stroke intervention by improving the person's self-selected walking speed.

Recently, we developed a unique gait training intervention for persons with chronic stroke that combines fast walking training with functional electrical stimulation (i.e. FastFES) to the dorsi- and plantarflexor muscles. Greater plantarflexor muscle activation has been hypothesized to improve walking speed through greater forward propulsion¹⁵ and fast treadmill training has been shown to improve self-selected walking speed post-stroke⁷. Given the relationship between increased walking speed and the energy cost of transport after stroke¹⁴, we hypothesized that an intervention combining fast treadmill walking with plantarflexor FES would result in an improvement in walking speed that would result in a decrease in the energy cost of transport. Alternatively, improvements in energy cost could occur independent of changes in walking speed. It is important to understand how the energy cost of transport improves after stroke so that optimal interventions can be developed. The purpose of this study was to examine changes in the energy cost of transport with a locomotor training intervention after stroke and to identify whether changes take place independent of changes in walking speed.

METHODS

Subjects

Persons with chronic stroke were recruited from local physical therapy clinics and senior centers. All subjects voluntarily gave written informed consent and the study was approved by the Human Subjects Review Board of the University of Delaware. All subjects were more than 6 months following a stroke, were able to walk continuously for 5 minutes at their self-selected speed, and were required to have enough passive range of motion so that their paretic ankle joint could reach within 5 degrees of the neutral position. Exclusion criteria included more than one previous stroke, congestive heart failure, peripheral artery disease with claudication, uncontrolled diabetes, shortness of breath without exertion, unstable angina, resting heart rate outside of the range of 40–100 beats per minute, resting blood pressure outside of the range of 170 mm Hg systolic and 60 mm Hg diastolic, inability to communicate with the investigators, pain in lower limbs or spine, total knee replacement, cerebellar involvement, neglect (star cancellation test¹⁶) and absence of sensation on the skin of the calf or leg of the paretic limb.

The data presented in this report are a subset of the data collected as part of a larger study investigating the effect of fast treadmill training combined with functional electrical stimulation (FES), termed FastFES.

Experimental Protocol

All subjects participated in testing before and after 12 weeks of the FastFES intervention comprising 36 sessions of locomotor training. This testing included clinical, motion capture and oxygen consumption (VO₂) testing. Only the data from the VO₂ testing sessions and selected clinical data are reported here. All subjects underwent a screening cardiac stress test prior to participation.

Training Protocol

Subjects participated in locomotor training 3x/week for a total of 12 weeks. Training speed was initially determined as the fastest speed the subject could maintain for 4 minutes of continuous walking. This was determined by starting the treadmill at the subject's self-selected walking speed and progressing upward with a goal of reaching their over ground fastest walking speed whenever possible. This speed was re-evaluated every 4 weeks and increased as possible using the same criterion. Each training session consisted of both treadmill and over ground walking. First, subjects completed up to 5 treadmill walking bouts that were each 6 minutes in duration. During each of these bouts, FES to the paretic ankle dorsi- and plantarflexor muscles was delivered during the first, third and fifth minute. During the second, fourth and sixth minute, FES was turned off and subjects were encouraged to practice walking with the same pattern as during the FES. This alternating pattern of FES delivery was designed to maximize potential motor learning¹⁷ and to minimize muscle fatigue. These bouts with FES were followed by a final bout of over ground walking without FES at the subject's fastest possible speed. During over ground walking subjects were encouraged to reproduce the same walking pattern as practiced with

the FES. Seated rest breaks (~5 minutes) were provided between consecutive walking bouts (Figure 1a).

Electrical Stimulation—Self-adhesive surface electrical stimulation electrodes were placed over the ankle dorsiflexor (2”X2”, TENS Products, Grand Lake, CO) and plantarflexor (2”X5”, ConMed Corp, New York) muscles (for details, see reference Kesar et al¹⁸). A Grass S8800 stimulator in combination with a Grass Model SIU8TB stimulus isolation unit was used to deliver electrical stimulation (Grass Instrument Company, Quincy, MA).

For both the dorsi- and plantar-flexor muscles, the stimulation amplitude was set using a 300-ms long, 30-Hz train with a pulse duration of 300- μ s (Figure 1b). For the ankle dorsiflexor muscles, stimulation amplitude was set with the subject seated and the foot hanging freely in a plantarflexed position. The stimulation train amplitude was gradually increased until a neutral ankle joint position (0°) or the subject's maximum dorsiflexion range of motion was achieved. The medio-lateral placement of the electrodes was adjusted to minimize ankle eversion / inversion (Figure 1b). For the ankle plantarflexor muscles, the stimulation amplitude was set with the subject standing in a position similar to terminal double support during walking with the non-paretic limb forward. The amplitude was increased until either the stimulation train produced a plantarflexor force sufficient to lift the paretic heel off the ground or until the subject's maximal tolerance was reached, whichever occurred first (Figure 1b).

Two compression closing foot switches (25-mm diameter MA-153, Motion Lab Systems Inc., Baton Rouge, LA) were attached to the sole of the subject's shoe of the paretic limb. One foot switch was placed under the fifth metatarsal head (forefoot switch) and the other under the lateral portion of the heel (hindfoot switch). The foot switches were used to control the timing of the FES during gait.

Timing of FES During Training—A customized, real-time, FES system consisting of a real-time controller (National Instruments, TX cRIO-9004), analog input module (NI 9210), and digital input/output module (NI9401) were used to control the Grass stimulator and deliver stimulation during the gait cycle^{18, 19}. The FES system delivered stimulation to the ankle dorsiflexor muscles during the time the foot switches of the paretic leg were not in contact with the ground. The ankle plantarflexor muscles were stimulated from the time the paretic foot's hindfoot foot switch was off the ground until the paretic foot's forefoot foot switch was off the ground. Thus, the timing of FES was designed to stimulate the ankle dorsiflexors during the paretic swing phase and the ankle plantarflexors during the paretic terminal stance phase, just prior to push-off (Figure 1c).

For FES during gait, novel variable frequency trains (VFTs) consisting of a high-frequency (200-Hz) 3-pulse burst followed by a lower frequency (30-Hz) constant frequency train were delivered^{18, 19}. We used these VFTs because they are physiological-based patterns that take advantage of the catch-like property of muscle and have been shown to enhance gait performance after stroke compared to the more traditionally used constant frequency train¹⁹.

Clinical Testing

As part of the larger study, subjects completed a battery of clinical tests. The results of the 6-meter walk test to measure short-distance self-selected (comfortable) and fastest walking speeds²⁰ and the 6-minute walk test (6 MWT) as a measure of walking endurance²¹ are reported here due to their relevance to the cost of transport.

VO₂ Testing

Prior to testing the CO₂ and O₂ analyzers were calibrated using standard calibration gases (16.00% O₂, 4.01% CO₂, balance nitrogen; Puritan Medical Products, Overland Park, KS). A pneumotachometer to assess expired gas volume (Hans Rudolph Inc.) was calibrated using a 3-L syringe (Hans Rudolph, Inc.). Subjects donned the mouthpiece of the metabolic measurement system, secured via a plastic headpiece placed on the subject's head, and a nosepiece placed over the nose. Subjects then sat quietly in a chair while 5 minutes of baseline expired air was collected for each subject. The volume of oxygen consumed was measured using a ParvoMedics TrueOne 2400 Metabolic Measurement System (Sandy, UT). During the pre-training assessment, the pre-training self-selected and fastest possible speeds (as determined for training) were tested. At the post-training assessment the pre-training speeds were tested in addition to the post-training self-selected and fastest possible speeds. Participants walked in five-minute bouts at each treadmill speed. Subjects wore an overhead harness during each bout for safety purposes only. No bodyweight support was provided and subjects were allowed to use the handrail. Subjects rested between each walking bout and testing was resumed only when heart rate, respiratory exchange ratio (RER), and VO₂ had returned to baseline levels. Walking was discontinued if heart rate exceeded 80% of the subject's age-predicted maximum (220-age) or if the Borg score exceeded 13 (indicating the subject was working at a moderately hard intensity)²².

Heart rate was monitored continuously using a Polar Heart Rate monitor (Polar Electro Oy, Kempe, Finland). This measurement was transmitted to a wireless receiver connected to the metabolic cart, where it was displayed continuously throughout each testing session. All data were sampled over the duration of each testing session at 15-second intervals. Subjects were determined to have reached a steady state of oxygen consumption when the variability in VO₂ measurement was less than 2.0 ml/kg/min over the last minute.

Data Analysis

VO₂ data collected over the last minute of each trial was averaged and normalized to body mass (mlO₂ · kg⁻¹ · min⁻¹). This data was then normalized to walking speed to yield the oxygen cost per unit distance walked (mlO₂ · kg⁻¹ · m⁻¹), which is generally referred to as the energy cost of transport^{9, 11–13}. Respiratory exchange ratio data averaged over the last minute of each bout were converted to their caloric equivalents using a caloric equivalent conversion chart²³ and multiplied by VO₂ (L · min⁻¹) to determine calories expended per minute (Kcal · min⁻¹). Each data point was then normalized to bodyweight and walking speed to yield caloric unit cost per meter walked (Kcal · kg⁻¹ · m⁻¹)²⁴. We chose to examine energy cost in terms of both oxygen cost and caloric cost because it has been suggested that the expression of metabolic cost in terms of caloric unit cost may be more sensitive to changes in speed than oxygen cost²⁴.

Our goal was to determine whether improvements in the energy cost of walking occurred following the locomotor training intervention and if so, whether they occurred independent of changes in walking speed pre- to post-training. In order to test this, we compared the energy cost of walking at subjects' pre-training and post-training self-selected walking speed. Then we examined the energy cost of walking at subjects' pre-training self-selected walking speed at both the pre-training and post-training time point (e.g.-an absolute speed tested at both pre and post-training). We reasoned that if improvements in the energy cost of transport occurred independent of walking speed, then we would see differences in energy cost from pre to post-training regardless of whether we tested at their pre and post-training self-selected speed or at an absolute speed.

Statistical Analysis

The Kolmogorov–Smirnov test was used to confirm that the data were normally distributed. The main variables of interest, Energy Cost of Transport ($\text{mlO}_2 \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$) and Caloric Unit Cost of Transport ($\text{Kcal} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$) were examined pre- and post-training using repeated measures ANOVAs with a within subjects factor of time (pre and post-training). Walking speeds and the distance covered during the 6 minute walk test were also examined pre-and post-training using repeated measures ANOVAs. Pearson product-moment correlations were used to examine the relationship between energy cost of transport and distance covered during the 6 minute walk test. Statistical significance was set at a $p < 0.05$.

RESULTS

The subjects' average age was 61.8 ± 8 years and average time since stroke was 42 ± 35.4 months (Table 1). Average self-selected walking speed prior to training was 0.57 ± 0.21 m/s.

For two subjects, oxygen consumption data at the pre-training self-selected walking speed was not available at post-training. Therefore, in order to examine changes in the cost of transport at an absolute speed, data from a speed collected at both pre and post-training session was utilized. For one subject, this was the post-training self-selected speed. For the other subject, this was data from an intermediate speed.

Self-selected walking speed increased following the intervention (Figure 2a & Table 1, $F=67.5$, $p < 0.001$, partial eta squared = 0.871) as did the fastest walking speed (Figure 2b, $F=40.9$, $p < 0.001$, partial eta squared = 0.804). Distance covered during the 6 minute walk test also increased from pre- to post-training (Figure 2c, $F=20.2$, $p = 0.001$, partial eta squared = 0.669).

There was also a strong correlation between the energy cost of transport at the subjects self-selected walking speed and the distance covered during the 6 minute walk test at both pre- and post-training (Figure 3, $r = -0.73$, $p = 0.01$; $r = -0.67$, $p < 0.05$, respectively).

Energy cost of transport at the subject's self-selected speed was lower following the intervention ($F=8.63$, $p = 0.015$, partial eta squared = 0.463; Figure 4a). The caloric cost of transport at the subject's self-selected speed also decreased after the intervention ($F=7.87$, $p = 0.019$, partial eta squared = 0.441; Figure 4b). In contrast, there were no changes between

pre-and post-training energy or caloric cost of transport values at an absolute speed measured pre-and post-training (Figures 4c&d).

DISCUSSION

The primary finding of this study was that following the FastFES locomotor training intervention, energy and caloric cost of transport (i.e.-cost per meter walked) at the stroke survivor's self-selected walking speed were significantly lower pre- versus post-training, while energy and caloric cost at an absolute walking speed did not change. This suggests that the improved energy cost of transport in this intervention was through improvements in the subject's self-selected walking speed. These results show that the improvements in self-selected walking speed following a locomotor training intervention are an important mechanism by which the energy cost of transport can be reduced post-stroke.

Results from a previous study showed that when asked to walk at a faster speed than their self-selected speed, chronic stroke survivors had a lower energy cost of transport (i.e.-improved economy)¹⁴. The present results extend these findings and demonstrate that when self-selected walking speed improves through training, the energy cost of transport decreases as a direct result of the increased speed. This improvement in energy cost through improving walking speed has potentially important functional consequences. Previous studies have shown that walking speed and walking activity are related in those with chronic stroke, such that those with slower walking speed take fewer steps per day²⁵. Our data indicate that walking speed is a strong mediating factor in the energy cost of walking and thus, it is possible that the reason that those who walk slowly walk less, is that it is more energy costly for them to walk. Previous studies have shown that walking activity and VO₂ peak are related in persons with chronic stroke such that those with higher VO₂ peak values take more steps/day²⁶.

The results for the energy cost and caloric cost of transport were similar. We chose to examine the caloric cost of transport because there is evidence to suggest it is more sensitive to changes in speed²⁴, which we hypothesized would change after training. The fact that both measures changed similarly reinforces the conclusion that the mechanism for the improved cost of transport after training was the improved self-selected walking speed.

The magnitude of the improvements in the energy cost of transport found in the present study are consistent with the improvements found following another locomotor training intervention in persons with chronic stroke⁷. However, it is not known whether the improvements in that study occurred independent of improvements in walking speed. In stroke survivors with slow walking speed, the greatest reduction in the energy cost of transport would be observed with improvements in walking speed and improvements in energy cost of transport that were independent of walking speed. To achieve maximal improvements in walking performance capacity, not only would the oxygen cost of transport need to improve, but so would maximal oxygen consumption and the lactate threshold²⁷. We chose to focus on the cost of transport because as mentioned previously, the energy cost of transport is 40–50% higher (i.e., worse) in those that have sustained a stroke⁵ and have impaired gait and we believed that the characteristics of this particular intervention (i.e., gait

training) would preferentially improve the oxygen cost of transport rather than increased maximal oxygen consumption or an increased lactate threshold.

Previous studies have found a relationship between cardiovascular fitness as measured by peak VO_2 and distance covered during the 6-minute walk test in persons with chronic stroke. We were therefore interested in whether improvements in the energy cost of transport would be accompanied by improvements in the six minute walk test. Distance covered during the 6-minute walk test did improve after training and these improvements (87.8 ± 64.7 m) exceed the minimal detectable change values determined for those with chronic stroke (52m)²⁸. Moreover, there was a strong correlation between the energy cost of transport versus distance covered during the 6-minute walk test at both the pre and post-training sessions. This suggests that the energy cost of walking plays a role in walking endurance in those with chronic stroke.

Limitations

The sample in this study is small. Given the large effect sizes observed, however, it would appear that the changes are robust. Nevertheless, future studies should examine changes in the energy cost of transport with locomotor interventions in larger groups of persons with chronic stroke.

Conclusions

Our results demonstrate that improvement in walking speed is the likely mechanism for improvements in the energy cost of walking following the FastFES locomotor training intervention. This result reinforces the results of other studies indicating the importance of designing interventions that improve walking speed for persons with chronic stroke.

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Figure 1.

A. Illustrates the pattern of electrical stimulation and walking during the training. B. Illustrates electrode placement and positioning for setting stimulation amplitude prior to training. C. Illustration of the components of the FES system: the footswitches provide timing information that is used by the real-time controller to control the delivery of FES to the subject.

Figure 2.

Clinical measures. A. Self-selected walking speed before (Pre) and after (Post) FastFES training. B. Fast walking speed before (Pre) and after (Post) FastFES training. C. Distance covered during the 6 minute walk test before (Pre) and after (Post) FastFES training.

Figure 3.

Correlation between the energy cost of transport at the subject's self-selected walking speed and the distance covered during the 6 minute walk test (6 MWT) prior to (A) and after (B) training. Each symbol represents data from a single subject.

Figure 4.

Cost of transport. A. Energy cost of transport at self-selected walking speed before (Pre) and after (Post) FastFES training. B. Caloric cost of transport at self-selected walking speed before (Pre) and after (Post) FastFES training. C. Energy cost of transport at an absolute walking speed before (Pre) and after (Post) FastFES training. D. Caloric cost of transport at an absolute walking speed before (Pre) and after (Post) FastFES training.

Table 1

Subject characteristics.

ID	Age	Hemiparetic side	Time since stroke (months)	Lower extremity Fugl-Meyer score	Pre-training self-selected speed (m/s)	Post-training self-selected speed (m/s)
S1	68	Left	22	23	0.63	1.03
S2	52	Left	110	24	0.89	1.07
S53	72	Right	68	13	0.49	0.72
S128	65	Right	18	18	0.49	0.72
S129	55	Right	54	17	0.49	0.80
S136	59	Right	12	13	0.31	0.49
S137	47	Right	8	15	0.49	0.49
S142	71	Left	9	19	0.40	0.49
S14	63	Right	95	23	0.92	1.04
S61	60	Left	32	12	0.41	0.65
S251	68	Left	34	31	0.79	0.95