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Walking speed and step length asymmetry modify the energy cost of walking after stroke

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Abstract

Background—A higher energy cost of walking poststroke has been linked to reduced walking performance and reduced participation in the community.

Objective—To determine the contribution of post-intervention improvements in walking speed and spatiotemporal gait asymmetry to the reduction of the energy cost of walking after stroke.

Methods—Forty-two subjects with chronic hemiparesis (> 6 months poststroke) were recruited to participate in 12 weeks of walking rehabilitation. The energy cost of walking, walking speed, and step length, swing time, and stance time asymmetries were calculated pre- and posttraining. Sequential regression analyses tested the cross-sectional (ie, pretraining) and longitudinal (ie, posttraining changes) relationships between the energy cost of walking versus speed and each measure of asymmetry.

Results—Pretraining walking speed ($\beta = -.506$) and swing time asymmetry ($\beta = .403$) predicted pretraining energy costs (${}_{adj}R^2 = .713$, $F(3,37) = 34.05$, $p < .001$). In contrast, change in walking speed ($\beta = .340$) and change in step length asymmetry ($\beta = .934$) predicted change in energy costs with a significant interaction between these independent predictors (${}_{adj}R^2 = .699$, $F(4,31) = 21.326$, $p < .001$). Moderation by the direction or the magnitude of pretraining asymmetry was not found.

Conclusions—For persons in the chronic phase of stroke recovery, faster *and* more symmetric walking after intervention appears to be more energetically advantageous than merely walking faster or more symmetric. This finding has important functional implications given the relationship between the energy cost of walking and community walking participation.

Keywords

Stroke; Gait; Symmetry; Oxygen Consumption

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As indicated by individuals who have sustained a stroke, the restoration of walking ability is an ultimate goal of rehabilitation[1], with a majority of individuals in the chronic phase of poststroke recovery identifying a reduced capacity to “walk farther” as a factor limiting engagement in the community[2]. Although a number of factors may limit an individual’s ability to walk farther, the increased energy cost of walking after stroke[3,4] is an important contributor. Indeed, stroke survivors who consume less oxygen per meter ambulated typically travel farther distances during the 6-minute walk test[5]. Interventions that reduce the energy cost of walking may therefore facilitate better long-distance walking function in people after stroke.

For slow walkers in the chronic phase of stroke recovery, faster walking speeds have been shown to reduce the energy cost of walking[6]. However, this knowledge does not sufficiently direct treatment as posttraining improvements in walking speed are often obtained through a variety of mechanisms, including better compensation for lost neuromotor control[7–10]. For example, to increase walking speed, subjects may compensate for deficits in paretic propulsion by strengthening existing kinetic asymmetries (e.g., a greater reliance on the nonparetic versus paretic limb for forward propulsion)[7,10] *or* become more symmetrical[11] – a sign of improved neuromotor control. The recovery of walking speed through compensatory strategies may be self-limiting as such strategies are associated with increased energy costs, a higher fall risk, reduced endurance, and slower speeds[12–15]. Even so, these compensatory strategies may be the result of processes optimizing other important parameters of walking (e.g., safety, pain, etc) in the face of an impaired motor system. A better understanding of how the strategy used to walk faster after intervention influences the cost of transport of persons in the chronic phase after stroke would direct future investigations and orient clinicians to important gait variables.

Spatiotemporal walking asymmetries are common kinematic deficits observed during poststroke locomotion[16–18]; however, the relationship between intervention-induced changes in walking asymmetries and changes in the energy cost of transport has yet to be examined. It is conceivable that in the chronic phase after stroke, walking patterns are already energetically optimized such that a reduction in walking asymmetry would not relate to a reduction in energy expenditure during walking[19,20]. However, understood within the framework of the step-to-step transition model[21,22], the unequal distribution of push-off and collision forces present during the double support phase of hemiparetic gait[23] would suggest that hemiparetic walking is not energetically optimal. Considering the relationship between spatiotemporal symmetry and walking kinetics after stroke[9], improvements in spatiotemporal asymmetry may relate to improvements in the energy cost of transport – as recently shown in neurologically-intact individuals[19,20] – through facilitation of a more equal division of pushoff and collision forces during walking. Moreover, when considering the heterogeneity of poststroke impairments, understanding to what extent the direction of step length asymmetry – e.g. subjects may take a larger step with either their paretic or non-paretic limbs – and the magnitude of asymmetry modifies the relationship between changes in symmetry and the cost of transport may provide insight important to clinical-decision making.

The primary purpose of this investigation was to determine if improvements in spatiotemporal asymmetry during walking contribute to a reduced energy cost of transport in persons poststroke beyond what is gained through only improvements in walking speed. We hypothesized that slower walkers and those with larger asymmetry would expend more energy during walking and that improvements in walking speed *or* asymmetry would contribute to reductions in the energy cost of walking. We also hypothesized that the *direction* of step length asymmetry pretraining would not moderate this relationship; however, based on prior work by Ellis[20] and Srinivasan[24], we hypothesized that the *magnitude* of asymmetry would such that improvements in asymmetry would be more meaningful to reducing the cost of transport in those with greater asymmetry.

METHODS

Subjects

The data presented are a subset of the data collected as part of a clinical trial studying treadmill-based locomotor training. Forty-two subjects were studied in this report (see Table 1 for subject characteristics). Subjects were recruited over a two-year period from health care facilities and patient support groups in the Delaware, New Jersey, and Pennsylvania areas. Subject inclusion criteria included a single cortical or sub-cortical stroke, a poststroke duration of at least six months, the ability to ambulate without the assistance of another individual, sufficient cognitive function to follow instruction and communicate with the investigators, the ability to walk for six minutes without orthotic support (e.g., without braces or ankle-foot orthoses), sufficient passive dorsiflexion range of motion to position the ankle in a neutral position with the knee extended, and sufficient passive hip extension to extend the hip ten degrees. Individuals were excluded from participating if they had a history of multiple strokes, cerebellar stroke, lower extremity joint replacement, bone or joint problems that limited their ability to walk, a resting heart rate outside of the range of 40-100 beats per minute, a resting blood pressure outside of the range of 90/60 to 170/90 mmHg, neglect and hemianopia, unexplained dizziness during the last 6 months, or chest pain or shortness of breath without exertion. All subjects signed written informed consent forms approved by the Human Subjects Review Board of the University of Delaware and received written medical clearance from their physician.

All testing described in the following sections were completed prior to (pretraining) and immediately following (posttraining) the completion of 12 weeks of locomotor training as described below.

Clinical Testing

Self-selected walking speed and the lower extremity motor domain of the Fugl-Meyer assessment scale[25] were measured for each subject to characterize pretraining impairment. All biomechanical and oxygen consumption data were collected at subjects' self-selected walking speeds, which were calculated as meters per second from the time recorded during the middle 6 meters of a 10-meter walk test[26]. Subjects were allowed the use of their regular assistive devices (e.g., canes) if necessary.

Measuring the Energy Cost of Walking

The methods utilized have previously been described[5]. Briefly, oxygen consumption testing was conducted under the supervision of a physical therapist and an exercise physiologist. Subjects walked five minutes on a treadmill at their self-selected walking speed as oxygen consumption (VO2) was measured via the ParvoMedics TrueOne 2400 Metabolic Measurement System (Sandy, UT). The majority of subjects held onto a handrail while walking on the treadmill. Subjects used a handrail if they normally utilized an assistive device (n=12) or if they felt unsafe walking on a treadmill (n=17). Handrail hold was consistent within and across trials. Subjects were only allowed to hold onto a handrail located at the side of the treadmill, which mimicked walking with an assistive device and placed less constraint on the anterior/posterior displacement of the body during walking.

Data were sampled at 15-second intervals over the duration of each walking trial. Steady state was defined as the period when the variability in VO2 was <2.0 mL/kg/min[27]. To calculate the energy cost of walking, VO2 data collected during the final minute of walking (ie, during steady state) were averaged and then normalized to body mass and walking speed. As such, the energy cost of walking reflects oxygen consumption per meter walked (ml O2/kg/m). Heart rate, blood pressure, and the Borg Scale of Perceived Exertion[28] were monitored during the testing.

Motion Analysis

Motion analysis sessions occurred on a different evaluation day. Kinetic and kinematic data were collected via an 8-camera motion analysis system (Motion Analysis 3D Eagle, Santa Rosa, CA, USA) when subjects attained their self-selected walking speed on a dual-belt treadmill instrumented with two independent 6-degree of freedom force platforms. Kinematic data were sampled at a rate of 100 Hz based on the motion of retro-reflective markers placed bilaterally on the heels. The average 3D residual for the camera calibration was between 0.25mm and 0.35mm. Vertical ground reaction forces were used to identify gait events (ie, initial contact and toe off). Step length, stride duration, stance time, and swing time were calculated bilaterally. Step length was defined as the distance between the leading limb's heel marker at initial contact and the contralateral limb's heel marker. Stride duration was defined as the time from one ipsilateral initial contact to the subsequent ipsilateral initial contact. Stance time was defined as the time between initial contact and toe off, normalized to stride duration. Swing time was defined as the time between toe off and initial contact, normalized to stride duration. Motion analysis data were processed using Visual 3D version 4.0 (C-Motion Inc., Germantown, MD, USA) and custom-written Labview (National Instruments Co., Austin, TX, USA) programs.

Intervention

Subjects were assigned to one of three treadmill and over ground training groups that were equivalent in structure: 1) walking training at a self-selected pace (SS), 2) walking training at the fastest speed maintainable for four minutes (FAST), and 3) FAST with the addition of functional electrical stimulation (FES) applied to the paretic limb's dorsiflexors and plantarflexors (FastFES). Greater detail on the FastFES intervention may be found in previous work from our laboratory[29]. Regardless of group, subjects completed 3 sessions per week for 12 weeks. Each session was comprised of up to 36 minutes of walking per session. Subjects were allowed rest breaks of up to 5 minutes between walking bouts. While walking on the treadmill, subjects were connected to an overhead harness system for safety; no body-weight was supported via the harness. Considering that the aim of this report was on studying how changes in speed and spatiotemporal asymmetry contribute to changes in the energy cost of walking in individuals poststroke, all subjects were grouped for the presented analyses – providing us with a greater range of data points from which these relationships could be elucidated. A forthcoming manuscript will provide group-specific results.

Data Management

Step length, stance time, and swing time walking asymmetries were calculated as follows:

a. ***Step Length Asymmetry:*** larger step length/(larger step length + smaller step length)

b. ***Stance Time Asymmetry:*** longer stance time/(longer stance time + shorter stance time)

c. ***Swing Time Asymmetry:*** longer swing time/(longer swing time + shorter swing time).

As such, for each measure, a value of 0.50 reflects perfect symmetry. For step length asymmetry, a value of 1.00 reflects a step-to gait pattern, and values greater than 1.00 reflect a walking pattern where one limb does not pass the other. To account for stride-to-stride variability, data from the first 15 strides collected were utilized in computing means for each measure of asymmetry. As such, the means computed from the 15 strides of walking sufficiently characterize the walking asymmetry of our subjects. Change-scores for the energy cost of walking and each measure of asymmetry were calculated as PRE minus POST so that positive values would indicate improvement.

Statistical Analyses

All statistical analyses were conducted in SPSS version 21. Sequential linear regression models were used to quantify the relationship of walking speed, stance time asymmetry, swing time asymmetry, and step length asymmetry to the energy cost of walking. Both cross-sectional (pretraining values) and longitudinal (change-scores) data were evaluated. Because both temporal measures of asymmetry – stance time and swing time – were highly correlated ($r = .959$, $p < .001$), only swing time asymmetry was included in the models to avoid multicollinearity. Secondary analyses were performed to test for moderation of 1) the relationship between changes in speed and changes in the energy cost of walking by changes in asymmetry, 2) the relationship between changes in asymmetry and changes in the energy cost of walking by the *direction* or 3) the *magnitude* of pretraining asymmetry. For all regression analyses, variables were centered to minimize issues related to multicollinearity. An examination of residuals for each of the regression models containing all the variables of interest was performed to determine the presence of outliers. Only for the longitudinal regression model was an outlier identified and removed. An alpha level of 0.05 was set as the threshold for statistical significance.

Cross-sectional and Longitudinal Analyses

A regression model predicting the energy cost of walking *pretraining* was generated by sequentially adding pretraining walking speed, swing time asymmetry, and step length asymmetry as independent variables. Walking speed was added first because of its established relationship as an important contributor to the energy cost of walking after stroke[6]. Swing time asymmetry was added before step length asymmetry because of its higher correlation to the energy cost of walking (r = .743 versus r = .555, both p < .001). Standardized (β) coefficients were tested to evaluate our hypothesis that slower walkers and those with greater asymmetry would have a greater cost of transport. Subsequently, a regression model was generated that predicted *changes* in the energy cost of walking from *changes* in walking speed and *changes* in measures of asymmetry. Change variables were added in the same order as in the pretraining model. For the moderated multiple regression analyses, the interaction terms of [change in asymmetry * change in speed], [pretraining asymmetry * change in asymmetry] and [pretraining asymmetry direction * change in asymmetry] were added to the final change-score model to assess moderation of the relationship between changes in walking speed and changes in the energy cost of walking by (1) change in asymmetry, (2) pretraining asymmetry magnitude, and (3) pretraining asymmetry direction, respectively. Significant interaction terms would indicate moderation. The unstandardized *(b)* regression coefficients generated from the pretraining and longitudinal analyses can be used to generate equations predictive of an individual's energy cost of walking or changes in the energy cost of walking, respectively.

RESULTS

Of the forty-two subjects recruited to this study, pretraining oxygen consumption data were not available for one subject due to technical issues during data collection and posttraining oxygen consumption data were not available for an additional four subjects due to logistical issues. Thus, pretraining analyses were conducted on the data from 41 subjects and change-score analyses were conducted on the data from 37 subjects. Of these 37 subjects, 19 subjects improved – defined as any change larger than zero – their swing time asymmetry, 28 subjects improved their step length asymmetry, 14 improved both swing time asymmetry and step length asymmetry, and 4 improved neither swing time asymmetry nor step length asymmetry. A broad range of impairment was observed with subjects presenting with a median (SIQR) self-selected walking speed of 0.76 (0.17) m/s and a median (SIQR) lower extremity Fugl-Meyer score of 25 (3.5). See Table 1 for subject characteristics and Table 2 for pretraining and change-score summary statistics.

Cross-sectional Analyses

Pretraining walking speed, swing time asymmetry, and step length asymmetry were each correlated to the energy cost of walking (all r's > .555 and p's < .001); however, for a regression model containing all three measures ($F(3,37) = 34.046$, $p < .001$, ${}_{\text{adj}}R^2 = .713$), only walking speed ($b = -.251$, $\beta = -.506$, $p < .001$) and swing time asymmetry ($b = .999$, $\beta = .403$, $p = .001$) independently predicted the energy cost of walking with walking speed being a stronger predictor (see Figure 1 and Table 3).

Longitudinal Analyses

A sequential regression model was used to determine the independent contribution of changes in walking speed, changes in swing time asymmetry, and changes in step length asymmetry to changes in the energy cost of walking (see Table 4). In the first block, change in walking speed predicted change in the energy cost of walking ($R^2 = .140$, $p = .025$). Adding change in swing time asymmetry in the second block did not improve the model ($\Delta R^2 = .055$, $p = .143$). In the third block, after adjusting for change in walking speed and change in swing time asymmetry, change in step length asymmetry predicted change in the energy cost of transport ($\Delta R^2 = .352$, $p < .001$). The addition of the [change in walking speed * change in step length asymmetry] interaction term in the final block further improved the model ($\Delta R^2 = .186$, $p < .001$). Neither the magnitude nor the direction of pretraining step length asymmetry were found to moderate the relationship between changes in step length asymmetry and changes in the cost of walking (both ΔR^2 ‘s < .02, *p’s* > .05) and were thus not included in the final model.

The final change-score model accounted for 73.3% of the variance in changes in the cost of transport (${}_{adj}R^2 = .699$, $F(4,31) = 21.326$, $p < .001$). Change in walking speed ($b = .163$, $\beta = .340$, t = 3.663, $p = .001$), change in step length asymmetry ($b = .584$, $\beta = .934$, t = 7.905, $p < .001$), and the interaction between change in walking speed and change in step length asymmetry ($b = 3.286$, $\beta = .529$, t = 4.654, $p < .001$) were significant predictors, with change in step length asymmetry being the strongest predictor. The significant interaction indicates that the relationship between changes in walking speed and changes in the energy cost of walking is moderated by changes in step length asymmetry (see Figure 2). Specifically, for those with a change in step length asymmetry greater than one standard deviation above the mean, there is a strong positive relationship between improvements in speed and improvements in the energy cost of walking. In contrast, for those with an average change in step length asymmetry, there is a weak positive relationship. Interestingly, for those with a change in step length asymmetry one standard deviation or greater below the mean, a negative relationship was observed. This suggests that without a concomitant improvement in asymmetry, walking faster may be energetically costly. Alternatively, walking faster may not have been energetically advantageous for these subjects with a small – ie, one standard deviation below the mean – post-intervention change in step length asymmetry because they were already walking at their energetic optimum prior to training.

DISCUSSION

The major finding of this study is that, beyond the influence of improvements in walking speed, intervention-induced improvements in step length asymmetry contributed to improvements in the energy cost of walking after stroke. Moreover, we demonstrate an interaction between changes in walking speed and changes in step length asymmetry such that faster *and* more symmetric walking yielded the largest reduction in energy consumption during walking. These findings support the development and implementation of interventions capable of increasing walking speed while simultaneously reducing the spatiotemporal asymmetries, particularly step length asymmetry, of persons with chronic stroke. The findings of this investigation have important functional implications given the relationship between the energy cost of walking and community walking participation[30].

Consistent with previous cross-sectional literature, pretraining temporal asymmetry was a stronger predictor of an individual’s walking performance than step length asymmetry[16]. However, as shown in the final change-score model (see table 4), changes in swing time asymmetry did not contribute to changes in the energy cost of walking. This interesting finding may reflect particular characteristics of the population studied, or of the different walking asymmetry parameters examined, or specific effects of our intervention. Most likely, it is a combination of each. That is, for chronic stroke subjects, swing time asymmetry may not be a variable easily modifiable in a manner that would directly influence walking economy. In contrast, step length asymmetry – while perhaps not as predictive of baseline energy costs – is more readily modifiable in a manner that influences walking economy. This suggestion is supported by previous studies showing that temporal asymmetries are more difficult to change compared to spatial asymmetries[31]. Indeed, while targeted training that improves the specific mechanisms underlying swing time asymmetry may be necessary to produce meaningful changes in swing time asymmetry, the present investigation demonstrates that meaningful changes in step length asymmetry are possible following non-directed treadmill training. In contrast, a recent study by Ellis and colleagues demonstrated that step time asymmetry was energetically costly[20]. An important difference between the study by Ellis et al (and others) and the present study is that previous studies have been limited to measuring the relationships resulting from some exogenous manipulation of mechanics (e.g., through split-belt walking, visual feedback, auditory feedback, etc...) rather than as a result of intervention. Thus, the present findings extend the work of Ellis et al and others by demonstrating a therapeutic relationship between changes in asymmetry – specifically step length asymmetry – and changes in the energy cost of walking after stroke.

Recent studies examining the energy cost of walking in neurologically-intact subjects provide insight into why improvements in energy expenditure may result from reducing the magnitude of step length asymmetry during poststroke walking. Based on the inverted pendulum model of locomotion, human bipedalism is thought to be energetically efficient due to the exchange of kinetic and gravitational potential energy as the center of mass arcs over the ipsilateral leg during single limb support[21,32]. However, during double support, mechanical work is necessary to redirect the velocity of the center of mass and transition to the contralateral leg[21]. This mechanical work accounts for approximately 2/3 of the metabolic cost of walking[33,34]. Prior work has shown that coordination of the push-off and collision forces that occur simultaneously during this step-to-step transition is critical to minimizing the work performed. Specifically, when the collision forces of the lead limb are of equal magnitude to the push-off forces of the trailing limb, work is at its minimum[33,34]. A recent study found that during hemiparetic walking, the push-off forces of the nonparetic limb exceed the collision forces of the paretic limb. Moreover, during double support, the push-off forces of the paretic trailing limb negatively correlate with the collision forces of the nonparetic leading limb[23]. Taking these findings together with the predictions of the step-to-step transition model, improvements in the energy cost of walking may result from reductions in step length asymmetry if such reductions facilitate an equalization of collision and push-off forces during double support. Future work is necessary to test this hypothesis and fully elucidate the mechanisms underlying the relationships observed in the present investigation.

The secondary analyses presented in this report may further inform future rehabilitation efforts. An *a priori* hypothesis for this investigation was that the magnitude of asymmetry pretraining would moderate the relationship between improvements in asymmetry and changes in the energy cost of transport. This was posited due to an expectation that for those already near symmetry, improvements in asymmetry would not be as meaningful as for those who were very asymmetric – a hypothesis supported by prior work done by Ellis[20], Srinivasan[24], and colleagues. However, this report provides evidence against moderation by pretraining asymmetry magnitude or direction, suggesting that regardless of the magnitude or direction of the asymmetry, reducing asymmetry will have a meaningful effect on the energy cost of walking after stroke.

This report demonstrates that individuals poststroke are capable of learning to walk more symmetrically in a manner that reduces energy expenditure. However, a question that remains is why was gait intervention necessary to induce the changes observed in our subjects? For those in the chronic phase of stroke recovery, it is likely that pretraining walking patterns reflected optimization processes from earlier phases of recovery. That is, rehabilitation during the earlier stages after stroke and the walking practice inherent to daily activity may have reinforced walking patterns that optimized another important aspect(s) of walking (e.g. balance) over walking efficiency. However, due to recovery, such asymmetric walking patterns may no longer be optimal. We posit that massed stepping practice in a challenging environment – as was provided during the interventions studied – may have been the catalyst necessary to induce a more economical walking pattern in this cohort of chronic stroke subjects with generally very little daily walking activity[35].

Limitations

A limitation of this study is that our subjects' energy cost of walking was computed from VO2 data collected during the fifth minute of walking while the symmetry data were computed from the first 15 strides of measured walking on a different day. The presence of within-session changes in asymmetry during VO2 testing may confound the interpretation of our results.

Conclusions

The present study supports the perception that a consequence of asymmetrical walking after stroke is a higher energy cost of walking. The study and development of poststroke gait interventions capable of improving walking speed while simultaneously reducing step length asymmetry appears to be a worthwhile direction for future study.

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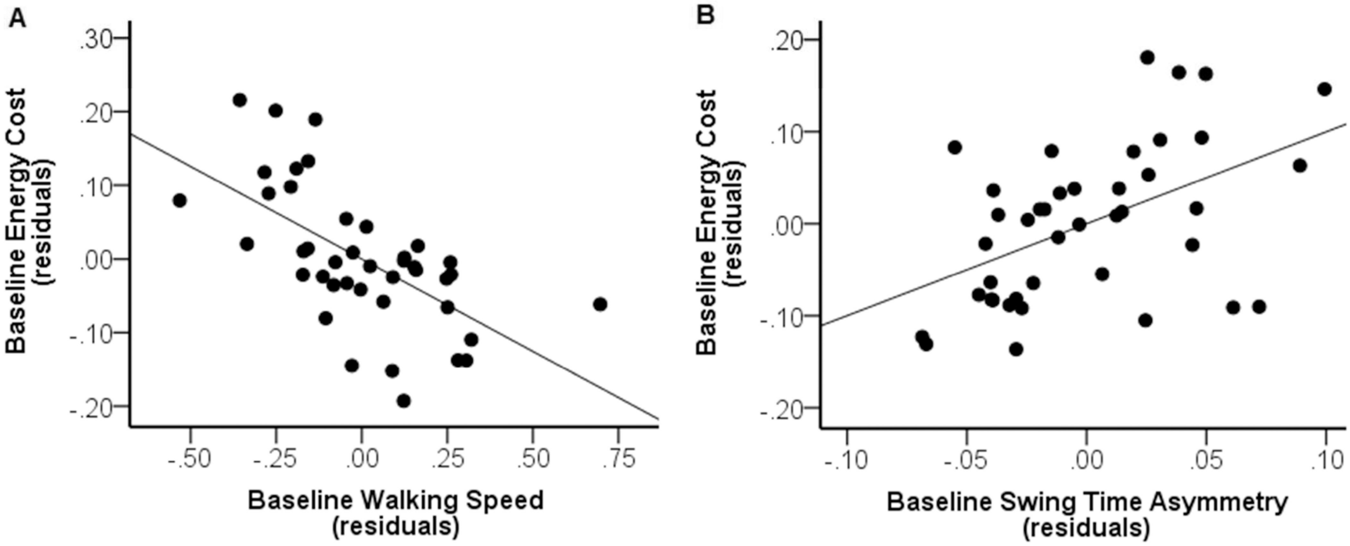

Figure 1.

Partial regression plots of the independent relationships between pretraining walking speed (panel A) and pretraining swing time asymmetry (panel B) versus the energy cost of walking when controlling for the non-significant predictor step length asymmetry. In panel A, the y-axis presents the residuals from regressing pretraining energy cost of walking on the independent predictors step length asymmetry and swing time asymmetry. In panel B, the y-axis presents the residuals from regressing the energy cost of walking on step length asymmetry and walking speed. On the x-axes are the residuals from regressing walking speed on the independent predictors step length asymmetry and swing time asymmetry (in panel A) and step length asymmetry and walking speed (in panel B). Faster walking speeds and less swing time asymmetry each independently predicted lower energy costs of walking.

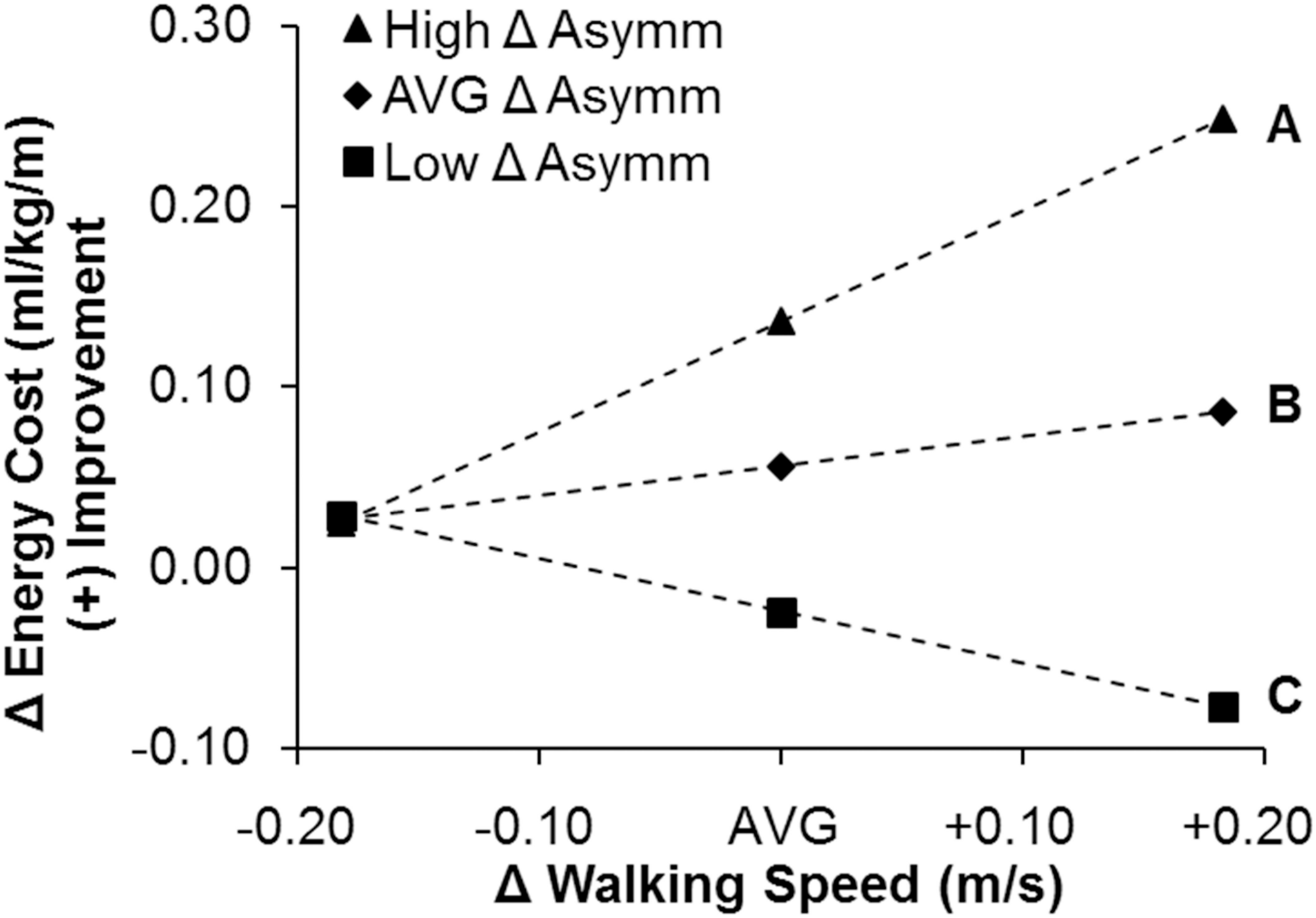

Figure 2.

A visual presentation of the relationship between changes in walking speed versus changes in the energy cost of walking as moderated by changes in step length asymmetry. Three regression lines are presented: the first represents this relationship for those with a high change in asymmetry (defined as a change of + 1 standard deviation) (A), the second for those with an average change in asymmetry (B), and the third for those with a low change in asymmetry (defined as a change of − 1 standard deviation) (C). Data points represent the average +/− 1 standard deviation of changes in walking speed (x-axis). Faster *and* more symmetric walking produced the largest reductions in the energy cost of walking after stroke (A).

Table 1

Subject (N=41) Characteristics

Variable	**Median (SIQR) or Frequency (%)**
Age, y	57.80 (4.5)
Time Since Stroke, y	1.66 (1.37)
Sex, male	65%
Side of Paresis, right	37.5%
Self-Selected Walking Speed, m/s	0.76 (0.17)
Lower Extremity Fugl-Meyer, Score	25 (3.50)

Table 2

Pretraining and Change-Score Median (SIQR) Values

PRETRAINING	CHANGE
Energy Cost of Walking (ml O2/kg/m)	
0.289 (0.067)	0.038 (0.040)
Self-Selected Walking Speed (m/s)	
0.77 (0.17)	0.18 (0.11)
Step Length Asymmetry	
0.526 (0.015)	0.008 (0.01)
Swing Time Asymmetry	
0.549 (0.031)	0.002 (0.014)

Table 3

Overview of sequential regression models predicting *pretraining* energy cost of transport for n = 41 subjects.

Model #	Predictors	Model p	ΔR^2	ΔR^2 p
1	Walking Speed*	.000	.602	.000
2	Walking Speed* Swing Time Asymmetry*	.000	.129	.000
3	Walking Speed* Swing Time Asymmetry* Step Length Asymmetry	.000	.004	.481

*indicates a significant independent predictor

Table 4

Overview of sequential regression models predicting *changes* in the energy cost of walking for n = 36 subjects.

Model #	Predictors	Model p	ΔR^2	ΔR^2 p
1	Δ Walking Speed*	.025	.140	.025
2	Δ Walking Speed* Δ Swing Time Asymmetry	.028	.055	.143
3	Δ Walking Speed* Δ Swing Time Asymmetry Δ Step Length Asymmetry*	.000	.352	.000
4	Δ Walking Speed* Δ Swing Time Asymmetry Δ Step Length Asymmetry* Δ Speed × Δ Step Asymm*	.000	.186	.000

*indicates a significant independent predictor