The Interplay Between Walking Speed, Economy, and Stability After Stroke

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Background and Purpose: Energy minimization is thought to underlie the naturally selected, preferred walking speed; however, people post-stroke walk slower than their most economical speed, presumably to optimize other objectives, such as stability. The purpose of this study was to examine the interplay between walking speed, economy, and stability.

Methods: Seven individuals with chronic hemiparesis walked on a treadmill at 1 of 3 randomized speeds: slow, preferred, and fast. Concurrent measurements of speed-induced changes in walking economy (ie, the energy needed to move 1 kg of bodyweight 1 ml O_2/kg/m) and stability were made. Stability was quantified as the regularity and divergence of the mediolateral motion of the pelvic center of mass (pCoM) during walking, as well as pCoM motion relative to the base of support.

Results: Slower walking speeds were more stable (ie, pCoM motion was 10% ± 5% more regular and 26% ± 16% less divergent) but 12% ± 5% less economical. Conversely, faster walking speeds were 9% ± 8% more economical, but also less stable (ie, pCoM motion was 17% ± 5% more irregular). Individuals with slower walking speeds had an enhanced energetic benefit when walking faster ($r_s = 0.96$, $P < 0.001$). Individuals with greater neuromotor impairment had an enhanced stability benefit when walking slower ($r_s = 0.86$, $P = 0.01$).

Discussion and Conclusions: People post-stroke appear to prefer walking speeds that are faster than their most stable speed but slower than their most economical speed. The preferred walking speed after stroke appears to balance stability and economy. To encourage faster and more economical walking, deficits in the stable control of the mediolateral motion of the pCoM may need to be addressed.

Video Abstract available for more insights from the authors (see the Video, Supplemental Digital Content 1, http://links.lww.com/JNPT/A416).

Key words: *economy, hemiparesis, speed, stability, stroke*

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INTRODUCTION

Energy minimization is posited to be a primary control objective that underlies the preferred walking speed of humans and other animals.[1,2] When individuals with intact neuromotor control walk at a comfortable pace, their naturally selected preferred walking speed approximates their most economical speed.[1,3] In contrast, the preferred walking speed of people with chronic poststroke hemiparesis is not only substantially slower, but also not their most economical (ie, if made to walk faster, people post-stroke require less energy per meter traveled).[4] Energy minimization does not appear to be the primary control objective underlying the preferred walking speed after stroke.

More economical walking is associated with increased mobility and community activity in patients with locomotor impairments[5-7]; however, speed-induced deficits in walking balance control may prevent people post-stroke from self-selecting faster and more economical speeds. Indeed, falling is common after stroke, with nearly half of ambulatory stroke survivors reporting repeated falls in the first 12 months after leaving the hospital.[8] A wide variety of clinical and laboratory-based measures have been used to assess poststroke balance control during walking.[9] Higher levels of gait variability have, in particular, been shown to be associated with deficits in dynamic balance and poststroke neuromotor impairment.[10] Though some gait variability is natural to walking,[11] individuals with poststroke hemiparesis walk with markedly more variability than healthy controls.[10,12]

Linear measures of gait variability based on the standard deviation of a gait parameter measured on a stride-to-stride

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All study participants provided consent for publication of data.

Group and individual subject data are located in the article figures and tables. Data are available on request.

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basis are common and useful but reduce gait cycle information to a single metric (eg, variability in stride times across gait cycles) and thus fail to quantify the stability of the overall gait pattern.[11] In their article on poststroke walking balance control, Kao et al[12] went beyond linear measures of gait variability to characterize dynamic instability during poststroke walking. More specifically, they combined a spatiotemporal variability analysis with a dynamic margin of stability analysis[13,14] and a nonlinear time series analysis of trunk motion.[11,15] They found that beyond increased gait variability, people post-stroke present with dynamic instability in the mediolateral control of the body during walking, as measured by a reduced margin of stability and increased divergence in the pattern of body motion across strides. Moreover, these measures of stability were affected by walking speed, with both faster and slower walking resulting in greater instability. These findings highlight the multidimensional nature of poststroke walking stability and the sensitivity of nonlinear and mechanical stability metrics to changes in speed.

In this study, we investigate the interplay between walking speed, dynamic stability, and economy after stroke. More specifically, we modulated the walking speed of people poststroke to be faster or slower than their preferred speed and examined the corresponding changes in walking economy and dynamic stability. We hypothesized that the preferred speed would balance walking economy and dynamic stability such that walking faster would be more economical but less stable, whereas walking slower would be less economical but more stable. A better understanding of the interplay among these factors will facilitate the advance of speed-targeting therapies that can improve health and quality of life after stroke.

METHODS

Study Participants

Seven community-dwelling individuals with chronic poststroke hemiparesis participated in this preliminary investigation of the interplay between walking speed, stability, and economy (Table). Inclusion criteria included more than 6 months after stroke, observable gait deficits, and the ability to walk on a treadmill without orthotic support. Exclusion criteria included cerebellar stroke, orthopedic and pain conditions that affect walking, inability to communicate with investigators, neglect or hemianopia, or unexplained dizziness. All procedures were institutional review board-approved and written informed consent was secured for all participants.

Data Collection

Study participants completed 2 visits. The first consisted of the 10-m walk test, the 6-minute walk test,[16] the Functional Gait Assessment,[17,18] and the lower extremity motor portion of the Fugl-Meyer[19] administered by a licensed physical therapist. The second visit began with a brief acclimation and warm-up on the treadmill, followed by 4 trials of treadmill walking. Study participants used a handrail located to the side of the treadmill if necessary for safety but were instructed to use no more than "light touch." If the handrail was needed for 1 trial, the participant was instructed to similarly use the handrail for all trials. Walking economy and stability data were collected concurrently during each trial. A 4-minute trial duration was targeted, but the trial duration was allowed to vary if more or less time was needed for a sufficient steady-state collection window (see the Outcomes of Interest subsection). Across trials, an average ± standard error duration of 4.02 ± 0.22 minutes was achieved.

Study participants were outfitted with an indirect calorimetry system (Oxycon Mobile, Yorba Linda, California) and retroreflective markers attached to the skin.[20] An 8-camera motion analysis system (Motion Analysis Corp, Santa Rosa, California) collected kinematic data with a sampling rate of 60 Hz. Heart rate and perceived exertion were continuously monitored during each trial and blood pressure was assessed before and after each trial. More specifically, a heart rate monitor worn around the chest provided continuous heart rate data and the study participant was instructed to immediately alert the physical therapist if perceived exertion exceeded 15 (hard) on the Borg Rating of Perceived Exertion scale.[21]

Across the 4 treadmill walking trials, 1 of 4 walking speeds within each subject's self-selected walking speed range was tested in random order. These speeds were based on the short- and long-distance clinical tests performed during visit 1. More specifically, subjects were tested at their:

(i) *Slow speed*—20% slower than their preferred walking speed
(ii) *Preferred speed*—comfortable speed measured during the 10-m walk test
(iii) *Fast-1 speed*—long-distance speed measured as the average 6-minute walk test speed
(iv) *Fast-2 speed*—maximum walking speed measured during the 10-m walk test

The fast-2 speed condition was particularly challenging for some study participants to maintain on the treadmill and,

Table. Study Participant Baseline Characteristics

Subject	Age, y	Chronicity, y	Mass, kg	Sex	Side of Paresis	FM (Score)	FGA (Score)
1	61	1.18	46	M	Left	30	19
2	30	2.95	80	M	Left	13	14
3	55	1.81	77	M	Right	22	19
4	65	1.43	90	M	Left	23	15
5	60	1.80	70	M	Right	18	11
6	61	12.34	97	M	Left	25	23
7	74	4.81	77	F	Right	33	24

Abbreviations: F, female; FM, lower extremity motor portion of the Fugl-Meyer scale; FGA, Functional Gait Assessment; M, male.

for 3 participants, the bout was cut short of the duration required for steady-state walking due to high heart rates and exertion. The fast-2 speed condition was thus not available for these 3 participants; data from the fast-1 condition were used for their fast speed analyses. For the remaining 4 study participants, data from their fast-2 speed condition were used. Thus, analyses of the fast-speed condition used the data collected from each individual's maximum tolerable speed.

Outcomes of Interest

The final 2 minutes of steady-state walking from the slow-speed, preferred-speed, and fast-speed trials provided the kinematic and metabolic data from which the walking economy and stability outcomes of interest were computed. Steady-state walking was identified in real time based on monitoring of metabolic data by an exercise physiologist and, in postprocessing, defined as the period when the standard deviation in oxygen consumption was less than 2.0 mL O_2/kg/min[22,23] with a respiratory exchange ratio of less than 1.0. Walking economy was computed as mass-normalized oxygen consumption per meter (ie, mL O_2/kg/m). Dynamic stability was measured using 2 time series signal analyses[24] and a margin of stability analysis[25] of the mediolateral motion (ie, position data) of the pelvic center of mass (pCoM):

(i) *Sample entropy* time series analysis[24] quantified the regularity and predictability of pCoM motion across strides. Sample entropy is a measure that quantifies walking regularity where a more predictable and stable system has a lower entropy value (more regular) and a more chaotic and less predictable system has a higher entropy value (more irregular).

(ii) *Maximum Lyapunov exponent (LyE)* time series analysis[24] using the Wolf method—due to its sensitivity to smaller datasets in older adults[26]—quantified patterns of divergence in pCoM motion across strides. A lower LyE indicates less signal divergence and thus a more stable system.

(iii) *Margin of Stability* analysis[27] quantified mechanical stability based on pCoM motion relative to the base of support. A larger margin of stability is thought to potentially indicate greater resistance to perturbation, though it is debated how changes in the measure should be interpreted.

When considered alone, less sample entropy, a lower LyE, or a larger margin of stability suggests better dynamic stability; however, because each of these measures may be affected differently when changing walking speed, we defined an increase in dynamic stability as an improvement in at least one measure, without a worsening in the others and a decrease in dynamic stability as a worsening in any one measure, regardless of changes in the others.

Statistical Analyses

The SPSS software package (IBM Inc, version 24) was used for all analyses. Friedman's test was used to test for differences in each outcome across the 3 speed conditions. If significant, post hoc 2-tailed Wilcoxon signed rank tests compared the preferred speed condition versus the slow speed and fast speed conditions. For these analyses, α was set to 0.05 and a Holm-Šídák correction was used to adjust for multiple post hoc comparisons (adjusted p-values are reported). As an exploratory analysis, Spearman's correlations tested if baseline abilities (ie, speed and sensorimotor function) were associated with the speed-induced changes in walking economy and stability.

RESULTS

Study participants were 60.5 ± 2.4 years old (median ± interquartile range), 1.8 ± 0.6 years post-stroke, 78.5 ± 7.8 kg, 14% female, and 57% left hemiparetic (Table). Their lower extremity Fugl-Meyer score was 22.5 ± 2.8 and their Functional Gait Assessment score was 17.0 ± 2.4.

Walking Speed and Energy Expenditure

Differences in speed were observed across the walking speed conditions ($\chi^2_{(2)}$ =14.0, $P = 0.001$) (Figure 1A). Preferred walking speed was a median 0.76 ± 0.19 m/s. Compared with the median preferred walking speed, the slow speed condition was 20.00% ± 0.07% slower ($z = 2.37$, $P = 0.035$) and the fast speed condition was 40.79% ± 10.22% faster ($z = 2.37$, $P = 0.035$). Differences in energy expenditure were observed across conditions ($\chi^2_{(2)}$ =14.0, $P = 0.001$). Energy expenditure at preferred walking speed was a median 14.12 ± 2.16 mL O_2/kg/min. When speed was reduced to the slow speed, energy expenditure reduced by 7.85% ± 6.13% ($z = 2.37$, $P = 0.036$). Conversely, when speed was increased to the fast speed, energy expenditure increased by 23.11% ± 4.44% ($z = 2.37$, $P = 0.036$).

Walking Economy

Differences in economy were observed across the speed conditions ($\chi^2_{(2)}$ =12.3, $P = 0.002$) (Figure 1B). Economy at preferred speed was a median 0.29 ± 0.07 mL O_2/kg/m. At the slow speed, economy worsened by 11.9% ± 5.5% ($z = 2.37$, $P = 0.036$). Conversely, at the fast speed, economy improved by 8.6% ± 8.1% ($z = 2.03$, $P = 0.043$).

Walking Stability: Dynamic Structure of pCoM Motion

Sample Entropy: Regularity of pCoM Motion

Differences in walking regularity, as measured by the sample entropy of the pCoM's mediolateral motion, were observed across the speed conditions ($\chi^2_{(2)} = 13.6$, $P = 0.001$) (Figure 1C). Regularity at preferred speed was a median 0.24 ± 0.01. At the slow speed, walking became 10.27% ± 4.50% more regular ($z = 2.23$, $P = 0.034$). Conversely, at the fast speed, walking became 16.96% ± 5.28% more irregular ($z = 2.38$, $P = 0.034$).

Maximum Lyapunov Exponent: Divergence of pCoM Motions

Differences in the divergence of the pCoM's mediolateral motion, as measured by the LyE, were observed across the speed conditions ($\chi^2_{(2)} = 11.1$, $P = 0.004$) (Figure 1C). LyE at preferred speed was 1.54 ± 0.24. At the slow speed, LyE was reduced by 26.11% ± 16.01% ($z = 2.37$, $P = 0.036$).

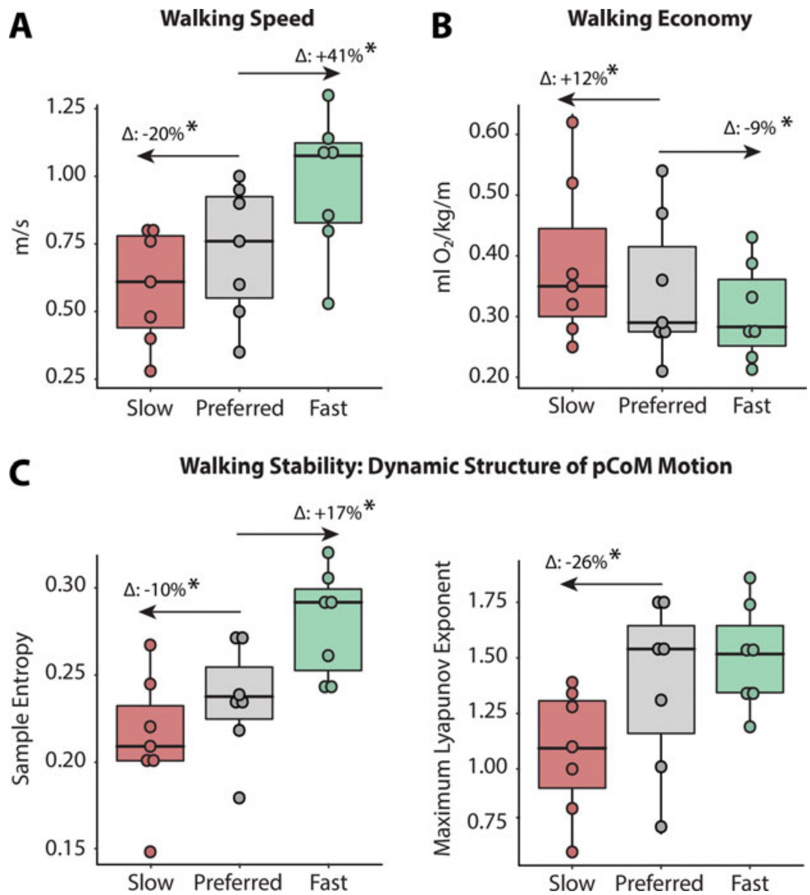

Figure 1. Effects of walking speed on economy and stability. (A) The 3 walking speeds tested were designed to test the functional speed range of each individual. (B) Walking economy was made worse when study participants walked slower than their preferred walking speed and made better when study participants walked faster than their preferred walking speed. (C) The stability of the mediolateral motion of the pelvic center of mass (pCoM) was measured at each speed using nonlinear time series analyses: the sample entropy (a measure of signal regularity) and maximum Lyapunov exponent (a measure of signal divergence). Both measures improved when study participants walked slower than their preferred walking speed (ie, reduced sample entropy and reduced maximum Lyapunov exponent), whereas walking regularity was worsened (ie, increased sample entropy) when study participants walked faster than their preferred walking speed. *$P < 0.05$. This figure is available in color online (www.jnpt.org).

Conversely, at the fast-speed, LyE was not observed to significantly change ($z = 1.01$, $P = 0.310$). However, consistent with the findings of the sample entropy analysis, 5 of the 7 subjects *increased* LyE with faster walking (by a median 20.9% ± 7.6%), whereas 2 subjects *reduced* LyE (by a median 18.3% ± 2.5%) (see Figure 2).

Walking Stability: Margins of Stability

Differences in the mediolateral margins of stability during paretic and nonparetic steps were not observed across the walking speed conditions (nonparetic: $\chi^2_{(2)} = 5.6$, $P = 0.062$; paretic: $\chi^2_{(2)} = 7.0$, $P = 0.37$) (Figure 3).

Correlates of Speed-Induced Changes in Walking Economy and Stability

Study participants' preferred speed strongly correlated with the changes in economy that resulted from walking *faster* than preferred speed ($r_s = 0.96$, $P < 0.001$) (Figure 4A). Moreover, sensorimotor function strongly correlated with the changes in LyE resulting from walking *slower* than preferred speed ($r_s = 0.86$, $P = 0.01$) (Figure 4B). No other significant correlations were observed.

DISCUSSION

Our study of the interplay between walking speed, stability, and economy after stroke suggests that people post-stroke may walk slower than their most economical speed to avoid a *stability* penalty, while also walking faster than their most stable speed to avoid a *metabolic* penalty. Indeed, a consistent pattern of speed-induced changes in economy and stability was observed at both the group level (see Figure 2) and the level of individual subjects (see the Individual Subject Responses subsection), with the preferred walking speed of people post-stroke appearing to balance, not maximize, stability and economy. That is, though people post-stroke may be

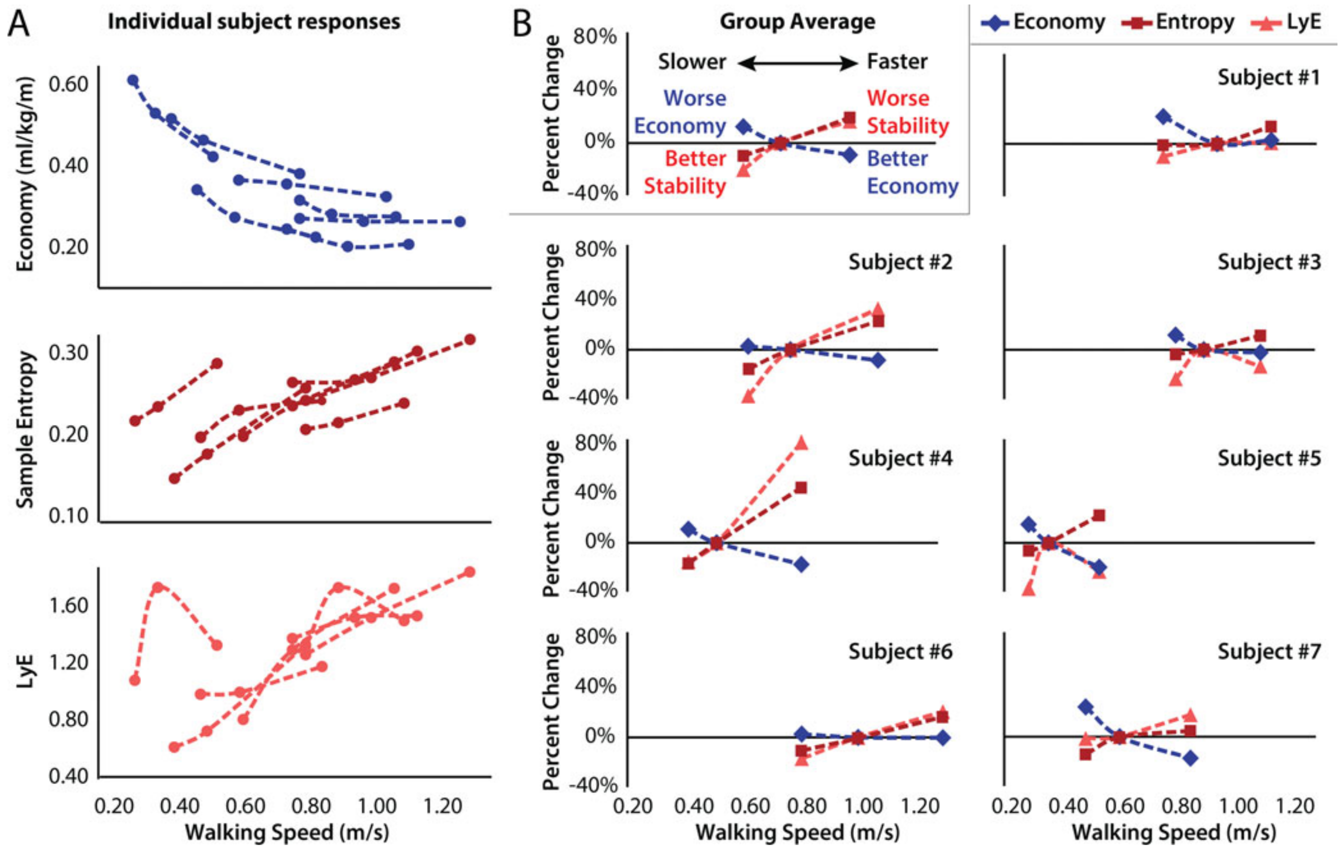

Figure 2. Individual subject responses on a per-variable (A) and per-subject (B) basis. In panel B, group and individual subject results are shown for the relative changes in walking economy (blue), sample entropy (dark red square), and Lyapunov exponent (LyE) (light red triangle) resulting from walking slower and faster than preferred walking speed. On the y-axis, negative values (ie, values below zero) indicate an improvement (ie, more economical or more stable walking), whereas positive values indicate worsening (ie, less economical or less stable walking). On the x-axis is the absolute walking speed, with the middle speed being the self-selected preferred speed, the left speed being the slow speed, and the right speed being the fast speed. On the y-axis is the percent change in each outcome. The x- and y-axis values repeat across panels. This figure is available in color online (www.jnpt.org).

capable of walking at faster, more economical speeds, they may not due to decreased stability when walking at those faster speeds. And though walking slower may increase stability, people post-stroke may avoid even slower speeds due to worsening economy (see the Video, Supplemental Digital Content 1, http://links.lww.com/JNPT/A416, Video Abstract). Further study of the interplay between speed, economy, and stability is warranted. Indeed, individuals' day-to-day movement experiences, which are shaped by the physical and social demands of their home and community environments and recent experiences with gait interventions, may further explain the effect that speed modulation has on stability and economy.

Individual Subject Responses

All subjects followed the same general pattern of improved stability and a worsening (or minimal change) in economy with slower walking, and reduced stability and an improvement (or minimal change) in economy with faster walking. To provide additional insight into the interplay between speed, economy, and stability after stroke, in the following 2 paragraphs we examine the cases where speed modulation had a minimal effect on walking economy.

For subjects 1, 3, and 6, though walking faster resulted in worsening stability, economy did not improve as expected. For these individuals, avoiding a stability penalty may underlie, at least partly, a preferred walking speed that is slower than the speed they can achieve, but other factors likely contribute. For example, these 3 subjects were the *fastest* in the study cohort (see Figure 4A) and, consistent with prior work[4] (see the Walking Economy: Relationship to Preferred Walking Speed and Sensorimotor Impairment subsection for a detailed description), this may have contributed to the lack of metabolic incentive to walk faster. That is, in people post-stroke, there may be a speed threshold where walking faster is not only biomechanically disadvantageous (ie, due to worsening stability), but also not advantageous (ie, no improvement in economy). Future work is warranted to examine

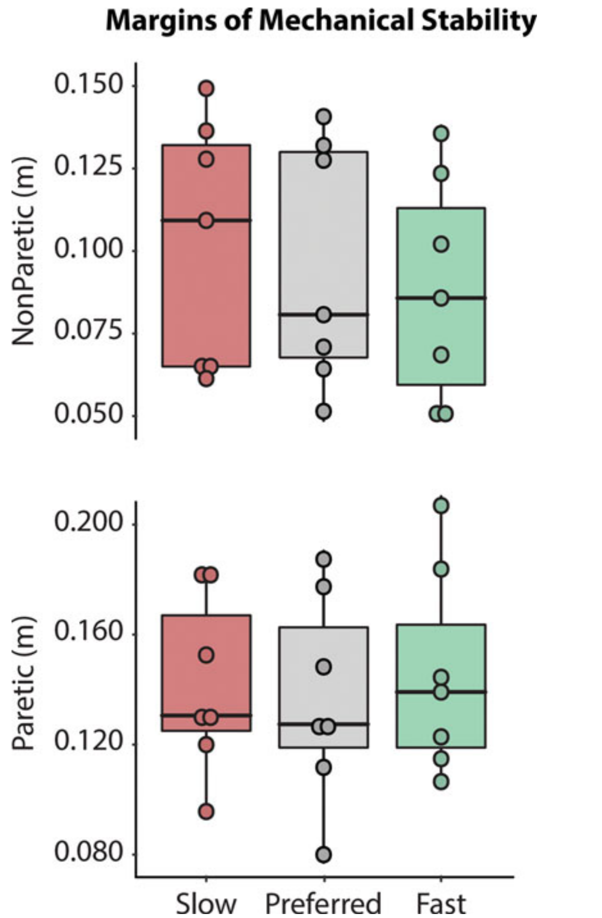

Figure 3. Mediolateral margins of stability during paretic and nonparetic steps were not observed to differ across walking speeds. This figure is available in color online (www.jnpt.org).

how therapeutic and orthotic interventions may affect the interplay between walking speed, stability, and economy in these faster, but still impaired, individuals post-stroke.

For subjects 2 and 6, their preferred walking speed was less stable than their slow speed, but this preference for a less stable walking speed was not explained by a metabolic benefit as would be expected. That is, for these 2 subjects, walking slower appears to provide a net gain: a stability benefit without a metabolic penalty. These cases support the notion that walking speed is likely not simply modulated to optimize economy and stability but may be balanced together with economy and stability. That is, walking speed is not just the output of a controller concerned with only stability and economy, rather is likely considered alongside stability and economy. Future work on the direct and indirect relationships between walking speed, stability, and economy is highly warranted.

Walking Economy

Minimizing the energy cost of walking is thought to be a locomotor control objective underlying the selection of the preferred walking speed.[1,28-30] The median preferred walking speed of our study participants was markedly slower than what has been reported in healthy older adults (ie, 0.76 vs 1.10 m/s).[31] As predicted by the U-shaped curve that describes the relationship between speed and economy,[28] our study participants' slower speed was associated with substantially worse economy (ie, 0.29 mL O2/kg/m vs 0.18 mL O2/kg/m[31]). In the face of poststroke neuromotor impairment, it is unclear whether the faster walking speeds observed in healthy individuals are likely to be energetically optimal after stroke; however, our subjects could achieve a median walking speed of 1.07 m/s, with this faster speed resulting in an approximately 10% improvement in economy (Figure 1B). That is to say, people post-stroke are able to walk at faster, more economical speeds, but prefer not to.

Walking Economy: Relationship to Preferred Walking Speed and Sensorimotor Impairment

We observed a strong positive relationship between preferred walking speed and the speed-induced changes in walking economy resulting from walking faster. More specifically, the energetic benefit to walking faster was attenuated in faster individuals and enhanced in slower individuals (Figure 2A, top left). Indeed, the 4 fastest subjects—who had an average fast speed of 1.15 m/s—improved walking economy by only 2.15%; in contrast, the 3 slowest subjects—who had an average fast speed of 0.73 m/s—improved walking economy by 18%. This finding is consistent with prior work showing that people post-stroke with fast speeds above 1.2 m/s do not improve walking economy when they walk faster.[4] Our study extends this prior work, showing an attenuated energetic benefit to walking faster even among individuals with a speed impairment—a finding that supports the idea that factors beyond speed influence economy.[22,30]

After stroke, not only do the majority of people self-select speeds slower than their most economical speed, but it is thought that the entire speed-economy curve is upwardly shifted due to metabolically expensive gait patterns.[22,32-36] That is, at any given speed, the walking economy of a person post-stroke is predicted to be worse than that of a neurologically intact individual. Indeed, even among individuals post-stroke who are able to achieve normal speeds, the cost of transport is nearly double[4] what is seen in healthy older adults.[37,38] While poststroke neuromotor impairment may result in gait patterns that increase the cost of transport, we did not observe a relationship between neuromotor impairment and the speed-induced changes in walking economy (Figure 4A, right). That is, regardless of baseline impairment, walking faster tended to improve economy and walking slower tended to worsen economy. Notably, we measured neuromotor impairment using the Fugl-Meyer scale; other measures may show a different relationship with speed-induced changes in economy and stability. For example, recent evidence in healthy individuals suggests that propulsion during walking balances economy[39] and stability,[40] and it is possible that different subsets of people post-stroke identified based on their propulsion function[41] may present with different responses to speed modulation.

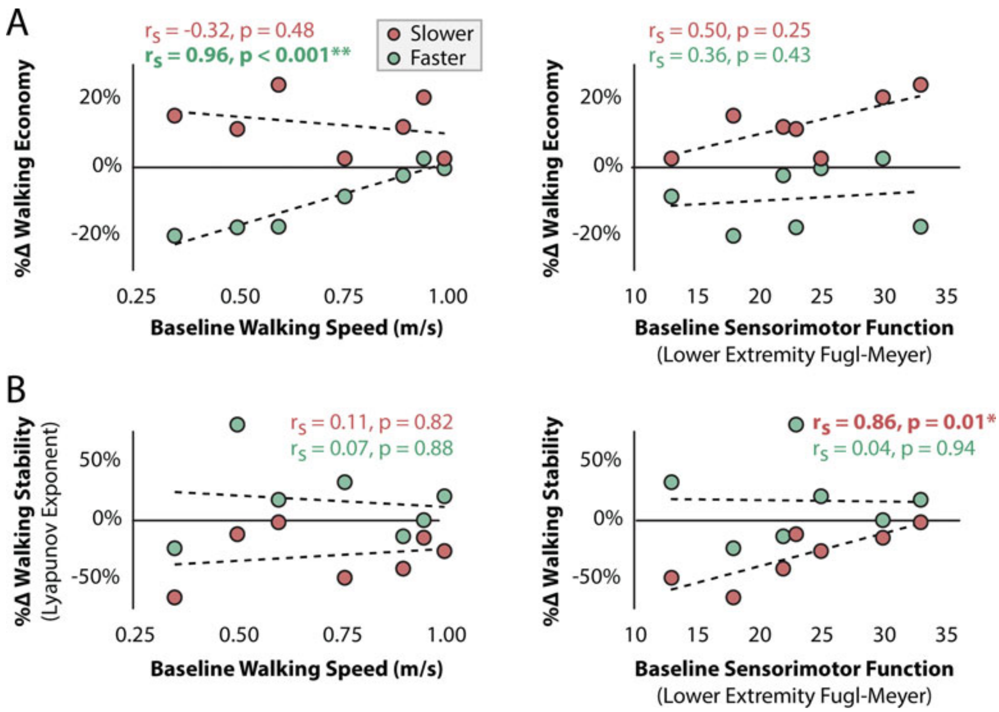

Figure 4. Relationships between baseline walking speed and sensorimotor function (as measured by the lower extremity Fugl-Meyer) versus the percent changes in (A) walking economy and (B) walking stability (ie, maximum Lyapunov exponent of pCoM mediolateral motion) resulting from walking faster (shown in green) versus slower (shown in red) than preferred walking speed. pCoM, pelvic center of mass. $^{**}P < 0.001$, $^{*}P < 0.05$. This figure is available in color online (www.jnpt.org).

The Interplay Between Walking Economy and Stability

It has been suggested that instead of minimizing energy utilization, the slower preferred walking speed of people post-stroke may result from processes directed toward enhancing stability.[12] If the preferred speed of people post-stroke optimized stability, then speed modulation (ie, walking faster or slower) should result in worsening stability. In contrast, we found that walking stability tended to improve when walking slower (whereas economy worsened) and tended to worsen when walking faster (whereas economy improved). Our finding that speed modulation results in the worsening of one of these factors and an improvement in the other suggests that the preferred speed of people post-stroke balances both stability and economy, not maximizes either.

Walking Stability: Relationship to Baseline Abilities

We observed a strong positive relationship between sensorimotor function and the speed-induced changes in walking stability resulting from walking slower (Figure 4B, right). More specifically, we found that the stability benefit resulting from walking slower was enhanced in more impaired individuals and attenuated in less impaired individuals. Interestingly, even though more impaired individuals gained even more stability from walking slower, this was found to come at the cost of worsening economy (Figure 4A, right). Together, these findings further support the notion that the preferred speed balances, not maximizes, economy and stability.

Walking Stability: Other Related Work

Our finding of slower walking resulting in improved stability and faster walking resulting in reduced stability is in agreement with prior work in healthy individuals.[42-44] However, these findings conflict with prior work by Kao et al[12] in people post-stroke, wherein a decrease in stability was reported when subjects were made to walk slower. Moreover, Kao et al[12] reported a reduction in the mediolateral margin of stability with faster walking, whereas we found that the margin of stability was not significantly affected by walking speed. The 2 studies share many similarities (ie, methods, outcomes, and sample size); however, key differences in subject characteristics and testing methodology may explain the diverging findings and warrant further investigation. Most importantly, the poststroke cohort tested by Kao et al[12] was markedly faster (ie, an average speed of 1.0 ± 0.30 m/s, range: 0.55–1.35 m/s) and less impaired (ie, an average lower extremity Fugl-Meyer score of 27 ± 4, range: 20-34) than our study sample with an average speed of 0.76 ± 0.19 m/s (range: 0.35-1.00 m/s) and a Fugl-Meyer score of 23 ± 4 (range: 13-33). The importance of this difference is evident in our finding of attenuated changes in LyE with slower walking among less impaired individuals (Figure 4B, left). Indeed, we observed that the stability penalty due to walking slower was markedly reduced in individuals with higher Fugl-Meyer scores. Because the poststroke cohort in the Kao et al[12] study was markedly less impaired than the subjects in our study, this helps to explain the different response, warranting further study. Moreover, our finding that the margin of stability was not affected by walking speed, whereas the nonlinear time series analyses were, is noteworthy and requires further investigation. This finding may suggest that the margin of stability, which is a poorly understood (albeit important) gait parameter in patient populations, may be less sensitive to speed changes after stroke and not a key determinant of the preferred walking speed.

Limitations

Biomechanical testing was conducted on the treadmill to enable direct control of walking speed and to allow comparison to previous studies that used similar methods.[4,12] However, these findings may not extend to overground walking. Moreover, light touch of the handrail by some participants—though necessary for safety—has the potential to affect measures of stability. Indeed, handrail usage may have attenuated the stability decline observed with walking faster. That is, our results may underestimate the stability penalty associated with walking faster than preferred speed.

Another limitation is that minimal detectable change scores have yet to be established for the stability and metabolic measures evaluated in this study. However, several factors suggest that the observed differences were not simply due to measurement noise. Indeed, despite the random order that the speed conditions were tested across this highly heterogenous sample of individuals post-stroke, a consistent pattern of speed-induced changes was observed across variables: slower walking tended to improve stability and worsen economy, whereas faster walking tended to worsen stability and improve economy (Figure 2A). Moreover, the magnitude of the changes in stability and economy was relatively substantial (ie, ∼10% to ∼25%) and approximated the magnitudes observed in previous studies.[4,12]

The small sample size and focus on the chronic phase of poststroke recovery are other limitations of this study. Though the consistent response pattern observed in this highly heterogenous sample of 7 individuals post-stroke stroke increases confidence in the results, findings in the chronic phase of poststroke recovery may not extend to earlier phases; validation in a larger study sample spanning the continuum of stroke recovery would be valuable. Indeed, our finding that speed-induced changes in stability and economy were associated with subjects' baseline walking speed and degree of sensorimotor impairment strongly motivates follow-on work with larger sample sizes.

CONCLUSIONS

The findings of this study advance our understanding of the interplay between walking speed, stability, and economy in people with poststroke hemiparesis. The preferred walking speed after stroke appears to balance, not maximize, economy and stability. That is, although people post-stroke have the ability to walk at more economical (and faster) walking speeds, they self-select slower speeds that we observed to be more stable. Moreover, although they can achieve greater walking stability by walking slower, they self-select faster speeds that we observed to be more economical. To facilitate faster and more economical walking, deficits in the control of the mediolateral motion of the body during walking may need to be considered. Additionally, strong correlations between baseline neuromotor impairment and walking speed and the speed-induced changes in economy and stability highlight the need to account for the heterogeneous nature of poststroke neuromotor impairment.

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