Maximum Walking Speed Is a Key Determinant of Long Distance Walking Function After Stroke

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Background: Walking dysfunctions persist following poststroke rehabilitation. A major limitation of current rehabilitation efforts is the inability to identify modifiable deficits that, when improved, will result in the recovery of walking function. Previous studies have relied on cross-sectional analyses to identify deficits to target during walking rehabilitation; however, these studies did not account for the influence of a key covariate – maximum walking speed. **Objective:** To determine the relationships between commonly studied poststroke variables and the long-distance walking function of individuals poststroke when controlling for maximum walking speed. **Methods:** Correlation analyses of cross-sectional data from 57 individuals more than 6 months poststroke measured the relationships between standing balance, walking balance, balance self-efficacy, lower extremity motor function, and maximum walking speed versus long-distance walking function. For a subgroup of subjects who completed training, the relationship between changes in maximum walking speed versus changes in long-distance walking function was assessed. **Results:** Each measurement of interest strongly correlated with long-distance walking function (*r*s from 0.448 to 0.900, all *P*s $\leq$ .001); however, when controlling for maximum walking speed, none of the other measurements remained related to long-distance walking function. In contrast, when controlling for each of the other measurements, maximum walking speed remained highly related. Moreover, changes in maximum walking speed resulting from training were highly related to changes in long-distance walking function ($r = .737$, $P \leq .001$). **Conclusions:** For individuals in the chronic phase of stroke recovery, improving maximum walking speed may be necessary to improve long-distance walking function.

Key words: *determinants, gait, hemiparetic walking, hemiparesis, stroke, rehabilitation, walking function, speed*

For the majority of individuals who have sustained a stroke, the restoration of walking ability is the ultimate goal of rehabilitation.[1] Impaired walking ability has been linked to a delayed hospital discharge to home,[2] a delayed return to work,[3] and limited participation in the community.[2] However, despite a focus on functional recovery during rehabilitation, residual walking deficits that increase the energy cost of walking and the likelihood of falls often persist.[2,4-6] A major limitation of current rehabilitation efforts is our inability to identify modifiable deficits that, when improved, will result in the recovery of walking function. A better understanding of this relationship would shape the development of targeted gait interventions[7,8] and enhance our ability to improve the walking function of individuals after stroke.

Recent studies have recommended targeting specific deficits during poststroke rehabilitation based on correlative and regression analyses of cross-sectional data.[9–19] However, basing interventions on the findings of such analyses may be problematic if key covariates are not controlled. For example, although lower extremity strength,[11,12,14,15,19] motor function,[18,19] and spasticity[19] have been shown to correlate with poststroke function, studies controlling for other variables have shown that they do not independently contribute to poststroke function.[9–11,14,15] That is, other variables mediate their relationship to functional performance. While it may be difficult to control for all potential

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mediating variables during cross-sectional analyses, understanding their influence on the relationships studied is critical to the valid identification of deficits to target during rehabilitation.

A recent study by Bowden and colleagues demonstrated that of 10 measurements considered, only improvements in *short-distance* maximum walking speed and the paretic limb's contribution to forward propulsion (paretic propulsion) – a commonly studied biomechanical variable directly linked to walking speed – correlated to improvements in *short-distance* comfortable walking speed.[7] Preliminary work from our laboratory has suggested that the *short-distance* maximum walking speed of individuals poststroke, measured from the middle 6 meters of a 10-meter path as subjects walked as fast as they safely could, may be an important modifier of their *long-distance* ambulatory function.[20] Improved walking efficiency may be the mechanism by which better *long-distance* walking function, measured as the distance traveled during the 6-minute walk test,[21] may result from improvements in *short-distance* maximum walking speed. Indeed, previous work has shown that walking at a faster speed reduces the energy cost of walking after stroke.[6] However, previous studies have not accounted for the variability in maximum walking speed in their analyses of the relationships between walking deficits and long-distance walking function. Thus, whereas variables such as cardiovascular fitness,[12] lower extremity strength,[11,12,14,15] balance,[9,10,12,18,22] balance self-efficacy,[10] and lower extremity motor function[13] have been shown to correlate to the walking function of persons after stroke, the extent that subjects' maximum walking speed mediates their relationships to long-distance walking function is unknown. Understanding how commonly targeted poststroke variables relate to *long-distance* walking function when controlling for *short-distance* maximum walking speed would elucidate the best targets for walking rehabilitation programs. We hypothesized that, for persons in the chronic phase of stroke recovery, *short-distance* maximum walking speed would be the primary determinant of *long-distance* walking function.

Additionally, as cross-sectional studies only measure the degree that variables relate at a single moment in time, they are unable to identify whether a variable is modifiable through intervention in a manner that relates to improvements in function. That is, it does not necessarily follow from a strong cross-sectional relationship between a variable and a measurement of function that reducing the magnitude of the deficit in that variable for a lower functioning individual would improve their function. In contrast, longitudinal analyses that specifically examine the relationships between changes in particular variables versus changes in function (change-score relationships) provide insight into the potential functional impact, for an individual, of improvements in a deficit.[7,23,24] Thus, a secondary aim of this study was to determine whether improvements in maximum walking speed resulting from gait training related to improvements in long-distance walking function.

Methods

Subjects

The baseline data presented in this report reflect the data collected for the first 57 individuals that were recruited to participate in a clinical study at the University of Delaware. The change-score data presented reflect the data collected for a subset of these subjects (n = 31) who underwent 12 weeks of physical therapist–guided locomotor training. Subjects were recruited over a 2-year period from health care facilities and patient support groups in the Delaware, New Jersey, and Pennsylvania areas. This study was approved by the University of Delaware's institutional review board, and all subjects gave their informed consent prior to participating.

Inclusion criteria

Subjects were included if they had a history of a single cortical or subcortical stroke, a duration poststroke of at least 6 months, were able to ambulate without the physical assistance of another person but with observable gait deficits, were able to follow instructions and communicate with the investigators, were able to walk for 6 minutes at a self-selected walking speed without orthotic support, and were able to passively dorsiflex the ankle to a neutral position with the knee extended and passively extend the hip at least 10°.

Exclusion criteria

Individuals were excluded from participating if they had a history of cerebellar stroke, a history of lower extremity joint replacement, bone or joint problems that limited their ability to walk, a resting heart rate outside of the range of 40 to 100 beats per minute, a resting blood pressure outside of the range of 90/60 to 170/90 mm Hg, neglect and hemianopia, unexplained dizziness in the last 6 months, or chest pain or shortness of breath without exertion.

Intervention

Subjects participated in a 12-week treadmill and overground walking retraining intervention. Training consisted of walking on a treadmill at each subject's maximum walking speed. Subjects walked either without (Fast) or with functional electrical stimulation delivered to the paretic ankle plantar flexors during terminal stance and dorsiflexors during swing phase (FastFES). The FES was applied in an alternating pattern of 1-minute on to 1-minute off. Further details on the FastFES intervention can be found in previous work from our laboratory.[25] Subjects trained 3 times per week, with each session comprised of up to five 6-minute walking bouts on a treadmill and one walking bout over ground for a total of up to 36 minutes of walking. 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.

Variables of interest and rationale

Subjects underwent comprehensive clinical evaluations conducted by licensed physical therapists. The present investigation considered the 6-minute walk test (6MWT)[21] as its representative measure of walking function. This decision was based on the 6MWT being an excellent measure of poststroke walking capacity and community ambulation,[26,27] as indicative of community reintegration following stroke,[2,28] and as the most prominent area of difficulty poststroke.[2] Indeed, individuals with chronic stroke indicate a reduced ability to walk farther as a factor limiting engagement in the community.[29] Measures were considered as measurements of interest if they could be targeted through intervention to improve the distance traveled during the 6MWT. The Berg Balance Scale (BBS)[30] and the Functional Gait Assessment (FGA)[31] evaluate standing (BBS) and walking (FGA) balance and have good reliability and validity in individuals poststroke.[30,31] The Activities-specific Balance Confidence (ABC) scale[32] evaluates balance self-efficacy and has been shown to have good reliability and internal consistency in community-dwelling older adults[32] and internal and absolute reliability and construct validity in people during the first year poststroke.[33] The lower extremity motor function domain of the Fugl-Meyer Assessment Scale (LEFM) quantifies the impairments in lower extremity motor function[34] and has been shown to be highly reliable in persons poststroke.[35] Finally, maximum walking speed (MWS) (m/s) was determined via the 6-meter overground walk test.[36] Subjects were allowed the use of their regular assistive devices and orthotics during testing, if necessary.

Cross-sectional analyses

Statistical analyses were performed using the IBM SPSS 21 software package (IBM, Armonk, NY). Power analyses were conducted using G Power 3.1. The overall threshold for significance was set to $P = .05$. The Shapiro-Wilk test was used to determine data normality. To test our a priori hypothesis that maximum walking speed would be the primary determinant of long-distance walking function, correlation (zero-order) and partial correlation (first-order) analyses were performed. Specifically, Pearson *r* or Spearman rho correlation analyses – pending data normality – measured the zero-order relationships between 6MWT distance versus MWS, FGA, BBS, ABC, and LEFM performance. Subsequently, each measurement of interest was selected, in turn, as a control variable when determining first-order relationships. After a Bonferroni correction for the 25 comparisons performed, an alpha level of 0.002 was set as the threshold for significance for each zero- and first-order relationship considered.

Longitudinal analyses

To test our secondary hypothesis that improvements in maximum walking speed would relate to improvements in long-distance walking function, the changes following an intervention targeting maximum walking speed were studied. Baseline versus postintervention pair-wise comparisons were conducted to test whether changes in maximum walking speed and 6MWT distance followed the training. Group changes were also compared to known minimal clinically important difference (MCID) and minimal detectable change (MDC) scores. The relationship between changes in maximum walking speed and changes in 6MWT distance was determined using Pearson *r* correlation.

Results

Complete baseline (n = 57) and change-score (n = 31) data sets were available for all variables studied (see **Table 1** for subject demographics and characteristics). An a priori power analysis revealed that with 57 subjects, at an alpha of 0.002, this investigation would be powered at a level of 80% to detect a significant baseline R^2 of 0.24. With 31 subjects, at an alpha of 0.05, this investigation would be 80% powered to detect a significant change-score R^2 of 0.23.

Table 1. Subject demographics and characteristics

Variable	Mean (IQR) or frequency (%)
Baseline dataset (n = 57)	
Age, years	59.02 (54.23-64.91)
Time since stroke, years	1.71 (0.88-3.51)
Sex, male	58%
Side of paresis, right	35%
Self-selected walking speed, m/s	0.75 (0.55-0.97)
Lower extremity Fugl-Meyer score	23 (20-27)
Change score dataset (n = 31)	
Age, years	57.50 (54.59-63.83)
Time since stroke, years	1.81 (0.94-6.24)
Sex, male	65%
Side of paresis, right	32%
Self-selected walking speed, m/s	0.74 (0.60-0.94)
Lower extremity Fugl-Meyer score	23 (18.50-27.50)

Cross-sectional zero- and first-order correlation analyses

Zero-order analyses demonstrated strong relationships (*r*s from 0.448 to 0.900) between each measurement of interest and performance on the 6MWT. However, when controlling for maximum walking speed, marked reductions in the strength of each of the other measurements' relationships to 6MWT performance were observed with none of these first-order relationships being significant. Likewise, controlling for walking balance resulted in a marked reduction in the strength of each of the other measurements' relationships to the 6MWT – except for maximum walking speed, which remained very strongly related to the 6MWT. In contrast, when controlling for standing balance, only balance self-efficacy no longer related to 6MWT performance. Controlling for either balance self-efficacy or lower extremity motor function did not result in substantial changes in any of the other measurements' relationships to the 6MWT (see **Table 2**).

Despite both maximum walking speed and walking balance markedly altering the strength of the other measurements' relationships to 6MWT performance, maximum walking speed clearly mediated a larger portion of each measurement's contribution to 6MWT performance. Moreover, only maximum walking speed remained very strongly related to 6MWT performance regardless of which of the other measurements was controlled (see **Table 2**).

Longitudinal analyses

Both maximum walking speed and the distance walked during the 6MWT improved following the 12-week intervention period (see **Table 3**). The average change in 6MWT distance of 77 meters was larger than the established MDC of 54.1 meters.[21] The average group change in maximum walking speed of 0.20 m/s was larger than the established walking speed MCID of 0.17 m/s.[37] Changes in maximum walking speed following the intervention strongly correlated to changes in 6MWT distance [$r(31) = .637, P \leq .001$].

Outliers

Graphical inspection of the Δ6MWT versus ΔMWS (**Figure 1**) relationship revealed that only one subject substantially improved 6MWT distance (184 meters) but not maximum walking speed (0.01 m/s). This subject was beyond the 95% confidence interval for this correlation. When considering this subject as a statistical outlier and removing them from the analysis of this relationship, a markedly stronger correlation between changes in the 6MWT versus changes in maximum walking speed

[Pearson $r(30) = .737$, $P \le .001$] was observed (see **Figure 1**). Interestingly, this subject's baseline maximum walking speed (1.81 m/s) was the highest among all the subjects studied.

Table 2. Zero-order and partial (first-order) correlation coefficients for the relationships between long-distance walking function (6MWT) versus each measurement

	Deficits				
Analysis	**MWS**	**FGA**	**BBS**	**ABC**	**LEFM**
Zero-order 6MWT correlations	0.900* P = .000	0.785* P = .000	0.729*[a] P = .000	0.448*[a] P = .000	0.557* P = .000
First-order MWS controlled		0.326 P = .014	0.181 P = .181	0.096 P = .484	-0.099 P = .468
First-order FGA controlled	0.747* P = .000		0.249 P = .064	0.302 P = .024	0.336 P = .011
First-order BBS controlled	0.807* P = .000	0.563* P = .000		0.298 P = .026	0.431* P = .001
First-order ABC controlled	0.864* P = .000	0.729* P = .000	0.596* P = .000		0.476* P = .000
First-order LEFM controlled	0.853* P = .000	0.712* P = .000	0.615* P = .000	0.407* P = .002	

Note: 6MWT = 6-minute walk test; MWS = maximum walking speed; FGA = Functional Gait Assessment; BBS = Berg Balance Scale; ABC = Activities-specific Balance Confidence Scale; LEFM = lower extremity motor portion of Fugl-Meyer scale.

[a] Spearman rho correlation coefficient.

*$P \le .002$.

Table 3. Baseline and change score values

	Mean (*SD*) and 95% CI			
Variable	**Baseline**	**Change**	***T* statistic**	***P* value**
6MWT (m)	302 (134) 253-351	77 (63) 54-100	6.781	<.001
MWS (m/s)	1.00 (0.46) 0.83-1.17	0.20 (0.22) 0.12-0.28	5.111	<.001

Note: 6MWT = 6-minute walk test; MWS = maximum walking speed.

Discussion

The present investigation identifies the short-distance maximum walking speed of individuals poststroke as an important determinant of their long-distance walking function and as a variable modifiable through intervention in a manner that highly relates to improvements in long-distance walking function. Taken together, the cross-sectional and longitudinal analyses presented support the development and study of poststroke interventions targeting an individual's maximum walking speed. Indeed, considering the established relationship between long-distance walking function and ambulation in the community,[26–28] the addition of interventions targeting short-distance maximum walking speed to poststroke walking rehabilitation programs is worthwhile.

It is not surprising that maximum walking speed accounted for a considerable amount of the

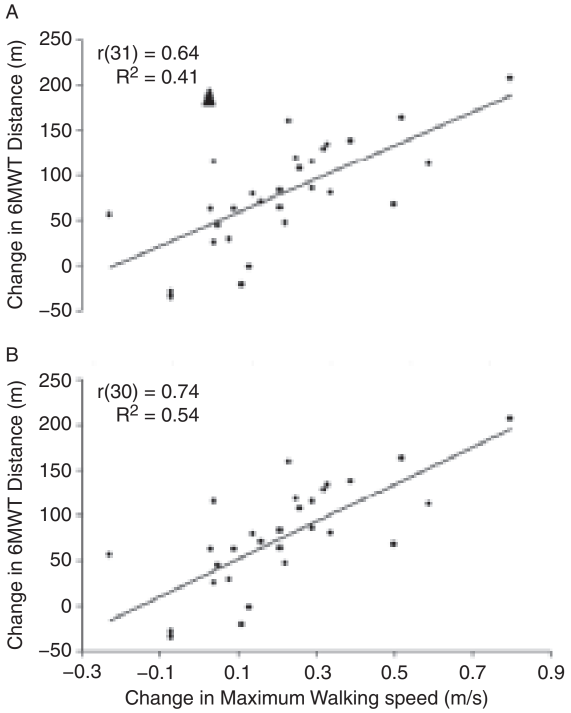

Figure 1. The relationship between changes in maximum walking speed (x-axis) and changes in long-distance walking function (6MWT) (y-axis) is presented with (**A**) and without (**B**) a statistically and clinically identified outlier – indicated by the triangle in panel A. Changes in maximum walking speed highly related to changes in 6MWT distance.

variance in a timed walking test such as the 6MWT. However, the predominant perception in the clinical community is that the 6MWT is a measure of walking endurance. That is, performance on the 6MWT is thought to be reflective of a person's ability to maintain a moderate amount of exertion over a period of time similar to the activities of daily living. Previous work has shown that the walking performance of community ambulators living with stroke deteriorates during the final minutes of the 6MWT.[38] To the extent that the psychosocial (eg, self-efficacy) or physical (eg, balance or motor function) factors studied may have been considered as contributors to worse performance during the 6MWT, it is surprising and important to learn that when controlling for maximum walking speed, none of the measurements studied remained related to performance on the 6MWT. Indeed, when controlling for maximum walking speed, subjects with excellent or poor self-efficacy, standing balance, walking balance, and lower extremity motor function performed similarly on the 6MWT.

Recommendations to target specific deficits during rehabilitation to improve poststroke walking function are commonly put forth based on the observed relationships between various measurements and function.[9-19] For example, Patterson and colleagues posited that clinicians should primarily target balance impairments during poststroke rehabilitation, followed by cardiovascular fitness, based on their finding that standing balance – as measured by the BBS – explained the largest portion of long-distance walking function variance for slower walking individuals poststroke and that cardiovascular fitness explained the largest portion for faster walking individuals.[12] Similarly, Pohl and colleagues found that standing balance significantly predicted long-distance walking function and concluded that balance was a "powerful modifier" of the long-distance walking function of persons poststroke.[13] Consistent with these and similar cross-sectional studies, the present study demonstrates strong zero-order relationships between standing balance – as well as other measurements – and walking performance; however, the partial correlation analyses of these same relationships indicate that maximum walking speed plays a key mediatory role and should therefore be considered when designing rehabilitation programs.

In contrast, Schmid and colleagues recently published a comprehensive examination of the relationships between multiple poststroke mobility variables – including maximum walking speed – and measures of activity and participation, identifying only "balance self-efficacy, not physical aspects of gait," as an independent contributor to activity and participation following stroke. Based on their findings, Schmid et al recommended addressing psychological factors related to balance self-efficacy "to obtain the best stroke recovery."[16] In the present study, we observe a marked reduction in the strength of the balance self-efficacy versus walking function relationship when controlling for maximum walking speed (from a zero-order $r = 0.448$, $P < .001$, to a first-order $r = 0.096$, $P > .05$). Moreover, controlling for balance self-efficacy did not modify the relationship between maximum walking speed and walking function. The inconsistency between the Schmid et al findings and those of the present study is likely a product of differences in the dependent variable studied. Indeed, the present study considers an objective measure of ambulatory function – the 6MWT – whereas Schmid et al consider self-report measures of activity and participation. Another likely explanation for this inconsistency is that the cohort of subjects studied by Schmid et al walked, on average, 0.30 m/s faster than the cohort in the present study. Certain thresholds likely exist for each of the measurements studied where improvements beyond such thresholds would not contribute to improvements in walking function. For example, the subjects studied by Schmid et al may not benefit from improvements in maximum walking speed because they already walk at a very fast pace. Indeed, the single subject identified as an outlier in the present investigation was the fastest walker pretraining (see Results section and **Figure 1**). In contrast, the other subjects studied in the present investigation may benefit from the targeting of maximum walking speed until they achieve a certain speed threshold, at which point, modifying the target of rehabilitation efforts to balance self-efficacy may indeed facilitate the best stroke recovery.

The findings of the present investigation may not extend to the rehabilitation of individuals in the earlier phases poststroke. For example, Pohl and colleagues demonstrated that in individuals an average of 75 days poststroke, gains made in the 6MWT were only predictable by gains in balance for those unable to ambulate more than 213 meters. In contrast, only gains in peak VO_2 and lower extremity motor function were predictive for individuals able to walk further than 213 meters.[24] However, Pohl et al noted that only 16% of 6MWT variance was accounted for by gains in balance for the lower performing individuals, and only 28% of 6MWT variance was accounted for by gains in peak VO_2 and lower extremity motor function for the higher performing individuals. In contrast, the present study demonstrates that 54% of the variance in 6MWT change is explainable by improvements in maximum walking speed. Although maximum walking speed was not measured by Pohl et al, considering the relationship between walking speed and the measurement of peak VO_2 on a treadmill,[39] it stands to reason that significant gains in maximum walking speed may have accompanied the observed gains in peak VO_2. A similar study by Kollen and colleagues of individuals in the acute phase of stroke recovery identified changes in standing balance as the most "important determinant" of improved walking function.[23] However, similar to the Pohl study, they were only able to account for 18% of the variance in functional ability with β regression coefficients < .09 for each determinant. An interesting future study would investigate whether the findings of the present study generalize to individuals in the earlier phases of stroke recovery.

Study limitations

This study only considered the relationships between the 6-minute walk test versus each subject's performance on the maximum walking speed test, BBS, FGA, ABC scale, and the LEFM. Thus, the relationships between the measurements studied versus measures of walking function other than the 6MWT, and the relationships between measurements other than those studied versus the 6MWT, are unknown.

Conclusions

The findings of the present investigation support the development and study of poststroke interventions targeting an individual's maximum walking speed. Previous studies recommending deficits to target during poststroke walking rehabilitation that did not account for the influence of maximum walking speed on the relationships studied should be considered cautiously.

Acknowledgments

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