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Frontal plane compensatory strategies associated with self-selected walking speed in individuals post-stroke

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Abstract

Background—Approximately two out of three individuals post-stroke experience walking impairments. Frontal plane compensatory strategies (i.e. pelvic hiking and circumduction) are observed in post-stroke gait in part to achieve foot clearance in response to reduced knee flexion and ankle dorsiflexion. The objective of this study was to investigate the relationship between self-selected walking speed and the kinematic patterns related to paretic foot clearance during post-stroke walking.

Methods—Gait analysis was performed at self-selected walking speed for 21 individuals post-stroke. Four kinematic variables were calculated during the swing phase of the paretic limb: peak pelvic tilt (pelvic hiking), peak hip abduction (circumduction), peak knee flexion, and peak ankle dorsiflexion. Paretic joint angles were analyzed across self-selected walking speed as well as between functionally relevant ambulation categories (Household <0.4 m/s, Limited Community 0.4–0.8 m/s, Community >0.8 m/s).

Findings—While all subjects exhibited similar foot clearance, slower walkers exhibited greater peak pelvic hiking and less knee flexion, ankle dorsiflexion, and circumduction compared to faster walkers ($P<.05$). Additionally, four of the fastest walkers compensated for poor knee flexion and ankle dorsiflexion through large amounts of circumduction.

Interpretation—These findings suggest that improved gait performance after stroke, as measured by self-selected walking speed, is not necessarily always accomplished through gait patterns that more closely resemble healthy gait for all variables. It appears the ability to walk fast is achieved by either sufficient ankle dorsiflexion and knee flexion to achieve foot clearance or the employment of circumduction to overcome a deficit in either ankle dorsiflexion or knee flexion.

Keywords

Gait; Stroke

Introduction

Approximately two out of three individuals post-stroke experience walking impairments (Mayo et al. 1999). Self-selected walking speed (SSWS) is typically used as a clinical indicator of gait performance and increasing SSWS is a common goal for gait retraining interventions after stroke (Jørgensen et al. 1995; Bohannon et al. 1991). It has been observed that individuals post-stroke have a wide range of SSWS yet the determinants of SSWS are unknown. Individuals post-stroke can be classified into three clinically meaningful categories according to gait speed: Household (<0.4 m/s), Limited Community (0.4–0.8 m/s), and Community (>0.8 m/s) where the community ambulators are the highest functioning (Perry et al. 1995; Schmid et al. 2007).

In addition to a range of walking speeds, a variety of altered kinematic patterns have been identified in post-stroke gait. These abnormal patterns include decreased knee flexion (Chen et al. 2005b) and ankle dorsiflexion during swing (Olney et al. 1991; Olney et al. 1994; Chen et al. 2005b). Limited ankle dorsiflexion and knee flexion during swing on the paretic side often result in the use of compensatory strategies (i.e. pelvic hiking and circumduction) to achieve foot clearance (Kerrigan et al. 1999; Kerrigan et al. 2000; Chen et al. 2005b). To date, the literature has focused on gait kinematics in the sagittal plane with only a small proportion highlighting the frontal plane, considerably limiting our understanding of compensatory strategies in post-stroke gait (Kim & Eng 2004; Kerrigan et al. 1999; Kerrigan et al. 2000). Compensatory strategies commonly observed during paretic swing phase include pelvic hiking, defined as a frontal plane elevation of the ipsilateral side of the pelvis (i.e., pelvic tilt), and circumduction, defined as excessive hip abduction of the ipsilateral limb (Kerrigan et al. 2000). It has been shown that these compensatory strategies are mechanically inefficient and energetically costly (Chen et al. 2005b) and therefore may have a negative impact on functional walking after stroke. It is not clear, however, whether specific compensatory strategies are associated with degree of walking function. One way to understand the role of such strategies is to examine the relationship between the kinematic patterns and walking speed after stroke.

The objective of this study was to investigate the relationship between SSWS and the kinematic patterns related to paretic foot clearance during post-stroke walking. We hypothesized that subjects with faster SSWS would have kinematics more similar to healthy individuals and rely less on inefficient compensatory strategies compared to subjects with slow SSWS. Specifically, we expected reduced hip hiking, reduced circumduction, increased peak knee flexion and increased peak ankle dorsiflexion in those post-stroke subjects with faster walking speeds.

Methods

A total of 21 individuals with post-stroke hemiparesis were recruited from the community and underwent comprehensive gait analysis at their self-selected walking speed. Inclusion criteria were as follows: chronic stroke involving cerebral cortical regions (>6 months post stroke), ambulatory but with residual gait deficit as defined as a visual gait abnormality assessed by a licensed physical therapist (including those who use a cane or walker), first (single) lesion (determined by an MRI or CT report), ability to walk for 5 minutes at self-selected paced speed, and age 18–80 years. Exclusion criteria were as follows: evidence of chronic white matter disease on MRI, congestive heart failure, peripheral artery disease with claudication, cancer, pulmonary or renal failure, unstable angina, uncontrolled hypertension (>190/110 mmHg), dementia (Mini-Mental State exam <22), severe aphasia, orthopedic or pain conditions, cerebellar signs (e.g. ataxic hemiparesis), or contraindications for MRI (e.g. metal implants). Signed consent forms approved by the Institutional Review Board of the University of Delaware were obtained for all participants.

Data collection

A set of 42 retroreflective markers was adhered to track trunk, pelvis, and lower extremity motion for walking trials. Subjects wore a safety harness connected to the overhead support of a split-belt instrumented treadmill (Bertec Corp., Columbus, OH, USA). This harness did not support body weight during trials but remained as a safety catch in case of a fall. Three-dimensional kinematic data was collected at 60 Hz using an 8-camera Motion Analysis system while subjects walked on the treadmill.

Familiarization to the treadmill was permitted at each participant's self-selected speed, determined prior to testing from a timed six-meter walking test. Two 2-minute treadmill-walking trials were recorded at the participant's self-selected speed. Rest periods between trials were provided as needed. Subjects walked without walking aids or ankle-foot orthoses (AFOs). If upper extremity stabilization was needed, instrumented handrails (Bertec Corp., Columbus, OH, USA) were used; however, subjects were instructed to use the handrails as little as possible.

Data Processing

Raw kinematic data of the pelvis and lower limb segments were post-processed in Cortex software (Motion Analysis Corp., Santa Rosa, CA, USA). Six degree of freedom static and dynamic subject-specific skeletal models were created in Visual 3D software (C-Motion, Inc., Germantown, MD, USA). Four joint angles of interest were calculated during swing phase for the paretic limb: peak pelvic tilt, peak hip abduction, peak knee flexion, and peak ankle dorsiflexion. Note that *peak pelvic tilt* is maximum frontal plane deviation of the pelvis in the lab coordinate system. During swing phase, pelvic tilt is positive when the ipsilateral swing side of the pelvis is elevated. *Peak hip abduction* is maximum frontal plane angle between the pelvis and the femur (Kerrigan et al. 2000). *Peak knee flexion* is defined as maximum sagittal plane angle between the femur and the shank, while *peak ankle dorsiflexion* is maximum sagittal plane angle between the foot and the shank. Vertical height

of the marker placed on the fifth metatarsal relative to the foot flat on the ground was measured at mid-swing as an indicator of foot clearance.

Statistical Analysis

Subjects were categorized into three ambulation categories based on his/her self-selected walking speed: Household (<0.4 m/s), Limited Community (0.4 m/s – 0.8 m/s), and Community (>0.8 m/s) (Perry et al. 1995). Non-parametric statistics were used in analysis because the data failed assumptions of normality. Spearman's rank correlations were performed between paretic joint angles and self-selected walking speed. Overall differences in paretic joint angles and foot clearance between subjects in each ambulation category were assessed using the Kruskal-Wallis test ($P<.05$). When results were significant across groups, individual group differences were then assessed using the Wilcoxon rank-sum test with a Bonferroni correction ($P<.017$).

Results

Of the 21 subjects who participated in this study, 8 were classified as Household ambulators, 7 as Limited Community ambulators, and 6 as Community ambulators. Other basic demographic and functional data can be found in Table 1.

Significant relationships were found between SSWS and peak ankle dorsiflexion ($Rho=0.73$, $P<0.001$), knee flexion ($Rho=0.71$, $P<0.001$) and pelvic tilt ($Rho=-0.61$, $P=0.0033$) (Figure 1). No relationship was found between SSWS and hip abduction. Knee flexion and ankle dorsiflexion increased with SSWS while pelvic tilt declined. Significant differences in peak paretic ankle dorsiflexion ($P=0.004$), knee flexion ($P=0.003$), and pelvic tilt ($P=0.02$) were observed across all ambulation groups (Table 2). Foot clearance did not differ between ambulation groups ($P=0.43$, Table 2). Differences in peak paretic knee flexion were found between Household and Limited Community ambulators ($P=0.004$, Table 2) and also between Household and Community ambulators ($P=0.001$, Table 2). Differences in peak paretic pelvic tilt were found between Household and Community ambulators ($P=0.01$, Table 2). Despite significant difference across groups in ankle dorsiflexion, no differences were detectable between individual ambulation groups after accounting for multiple post-hoc comparisons. This is likely due to insufficient power after splitting the population into smaller subgroups, as we saw a significant correlation between speed and ankle dorsiflexion across the entire population. Hip abduction was not found to be significantly different across ambulation groups.

Discussion

This study used motion analysis to investigate the relationship between kinematic mechanisms used to achieve foot clearance and self-selected walking speed among 21 individuals post-stroke. No difference in foot clearance was found between groups categorized according to SSWS; however, varied kinematic strategies were observed across groups to achieve foot clearance. Slower walkers were observed to have greater pelvic hiking (pelvic tilt) and less peak knee flexion, ankle dorsiflexion, compared to faster walkers. Additionally, four of the six fastest participants walked with the four largest

amount of circumduction. While the fast walkers had greater peak knee flexion, ankle dorsiflexion, and less pelvic tilt in overall group medians, inspection of individual subjects revealed foot clearance was achieved by either ankle dorsiflexion and knee flexion values comparable to healthy subjects (Perry 1992) or by employment of circumduction to overcome ankle dorsiflexion and/or knee flexion deficits.

Increases in paretic ankle dorsiflexion and knee flexion were observed with increased self-selected walking speed (Figures 1a,b). For comparison, the median paretic knee flexion for all subjects was 40.1° (range 10.6° – 63.2°) and is consistent with the average 37.8° (SD 9.8°) peak knee flexion range across all speeds reported in the literature (Chen et al. 2005b). The observed direct relationship between paretic knee flexion and SSWS is also consistent with literature (Kim & Eng 2004). Common post-stroke gait impairments, i.e. reduced ankle dorsiflexion and knee flexion, have been shown to contribute to reduced foot clearance ability and significantly decrease gait velocity (Lamontagne et al. 2002; Lin et al. 2006). Since knee flexion and ankle dorsiflexion assist with controlling the foot after push-off, greater paretic knee flexion and ankle dorsiflexion may in effect enable faster walking speeds by controlling foot clearance during swing.

Slow walkers employed pelvic hiking as a means of achieving foot clearance while fast walkers had minimal pelvic hiking values (Figure 1c). The median peak paretic pelvic hiking values for Household, Limited Community, and Community ambulators were 8.0°, 5.9°, and 3.1°, respectively. These values are inconsistent with the average frontal pelvis elevation of 0.2° in the study by Kerrigan et al. who measured frontal plane pelvis elevation and thigh abduction of post-stroke gait at midswing, noting that the peak elevation actually occurred before midswing (Kerrigan et al. 2000). Our values for both pelvic hiking and circumduction are measured as peak values throughout swing and are thus higher than reported previously by Kerrigan et al (2000). The study by Kerrigan et al. also reported pelvic hiking and circumduction values as one profile for all subjects, not considering differences in speed as a factor. All of the faster walkers (n=6) in our study exhibited reduced pelvic hiking, trending toward a healthy gait profile. In healthy gait, a 4-degree average pelvic *drop* of the ipsilateral pelvis during swing is observed (Perry 1992); in this study, however, all subjects had ipsilateral pelvic *elevation*. Even when minimal, pelvic hiking may be a compensatory strategy used to augment or facilitate foot clearance and increase speed in post-stroke gait in the slowest walkers.

To achieve foot clearance, the fast walkers either (1) had ankle dorsiflexion and knee flexion values comparable to healthy gait or (2) employed circumduction to overcome deficits in ankle dorsiflexion and knee flexion (Figure 1d). Excessive circumduction was observed in four of the six fast walkers. One study similarly identified excessive circumduction in 6 of the 8 fastest walkers with an average SSWS in the Community ambulator category (Kim & Eng 2004). Our median values of 4.9° and 9.3° for Limited Community and Community ambulator categories are consistent with Kerrigan's findings of an average 8.7° (SD 4.3°) of circumduction while the Household median of 3.4° lies just below this range (Kerrigan et al. 2000). This is in contrast to healthy gait, where the average circumduction for healthy gait is a 5° deviation from the neutral position (Perry, 1992). One Household ambulator, three

Limited Community ambulators, and four Community ambulators had circumduction values greater than healthy values.

There is not one universal mechanism used by the fast walkers to achieve foot clearance; individual subject evaluation must be completed. The four fast walkers with the excessive circumduction values exhibited poor ankle dorsiflexion and/or knee flexion with values below healthy gait. While circumduction was not a requirement to walk fast, it is a mechanism associated with the majority of the fast walkers and may represent a trade-off with hip hiking to achieve foot clearance. The two remaining fast walkers had ankle dorsiflexion and knee flexion values within the range of healthy gait and did not employ a compensatory mechanism. It appears the ability to walk fast is achieved by either sufficient ankle dorsiflexion and knee flexion to achieve foot clearance or the employment of circumduction to overcome a deficit in either ankle dorsiflexion or knee flexion.

As compensatory mechanisms, both pelvic hiking and circumduction have been shown to have exaggerated energy cost, though the relative cost between these two strategies has not been identified (Chen et al. 2005b; Lusardi et al. 2013). A large upper body postural sway favoring the non-paretic side, similar to pelvic hiking, has been shown to be indicative of a slower walking speed, with faster walkers exhibiting less lateral sway than slow walkers (Titianova & Tarkka 1995). Previous literature and this current study show that circumduction, however, does not follow an inverse relationship with SSWS in post-stroke gait (Kim & Eng 2004). A difference in energy cost may explain the observed discrepancy in trends between pelvic hiking and circumduction and SSWS in post-stroke gait. Greater shifts of the center of mass exhibited in pelvic hiking may require greater metabolic cost because pelvic hiking involves more displacement of the upper body than circumduction. Circumduction, conversely, may require less energy to employ than pelvic hiking due to the more distal and localized nature of the deviation. It is possible that pelvic hiking may lead to reduced SSWS more than circumduction due to the high metabolic cost of upper body involvement. Thus, reducing pelvic hiking during swing may improve efficiency and enable faster walking speeds in post-stroke gait.

While circumduction may cost less energy to employ, it may require more lower limb function. Thus, only higher functioning individuals post-stroke may be able to circumduct due to greater strength demands necessitated by this mechanism. It is, however, undetermined whether the mechanism of circumduction enables greater speed or the individuals employing circumduction are higher functioning and inherently faster. Functionally, the Community ambulators had the highest Fugl-Meyer Lower Extremity (FM_LE) scores; however there appears to be no direct relationship between circumduction and FM_LE, as the two fast walkers that did not circumduct did not have the highest FM_LE scores. This suggests that the Fugl-Meyer score may not be helpful when trying to understand why an individual with stroke selects a particular walking pattern.

The cross-sectional nature of this study limits the determination of cause-and-effect relationships between the kinematic patterns related to foot clearance and self-selected walking speed. Further research should investigate the energy cost of pelvic hiking versus circumduction as well as the strength requirements to improve understanding of why a

certain compensatory strategy is selected. In our study, 10 subjects utilized handrails for stabilization during data collection. Handrail holding in the post-stroke population has been found to increase single limb support time but not alter peak knee flexion during swing (Chen et al. 2005a). While peak knee flexion during swing may not have been altered, other gait parameters may have been affected by handrail usage and should be the focus of future studies. Although overground and treadmill kinematics are quantitatively similar in uninjured populations (Riley et al. 2007; Murray et al. 1985), the post-stroke population may respond uniquely to treadmill locomotion. Thus, results may not translate directly to overground gait.

Conclusions

This was the first study to investigate the associations between self-selected walking speed and frontal plane compensatory strategies (circumduction and pelvic hiking) that are commonly employed to achieve foot clearance in post-stroke gait. It was found that while the degree of foot clearance was similar across subjects, slower walkers and faster walkers achieved foot clearance differently. Slower walkers exhibited decreased knee flexion and ankle dorsiflexion and increased pelvic hiking. Faster walkers either had adequate knee flexion and ankle dorsiflexion or employed circumduction as a mechanism to overcome deficits in knee flexion or ankle dorsiflexion. Further research examining the energetic costs and strength requirements of pelvic hiking versus circumduction may help guide recommendations for therapeutic intervention.

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References

- Bohannon R, Horton M, Wikholm J. Importance of four variables of walking to patients with stroke. *International Journal of Rehabilitation Research*. 1991; 14(3):246–250. [PubMed: 1938039]
- Chen G, et al. Gait deviations associated with post-stroke hemiparesis: improvement during treadmill walking using weight support, speed, support stiffness, and handrail hold. *Gait and Posture*. 2005a; 22(1):57–62. [PubMed: 15996593]
- Chen G, et al. Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds. *Gait and Posture*. 2005b; 22(1):51–56. [PubMed: 15996592]
- Jørgensen HS, et al. Recovery of walking function in stroke patients: The copenhagen stroke study. *Archives of Physical Medicine and Rehabilitation*. 1995; 76(1):27–32. [PubMed: 7811170]
- Kerrigan DC, et al. Hip hiking and circumduction: quantitative definitions. *American Journal of Physical Medicine and Rehabilitation*. 2000; 79(3):247–252. [PubMed: 10821310]
- Kerrigan DC, et al. Spastic paretic stiff-legged gait: biomechanics of the unaffected limb. *American Journal of Physical Medicine and Rehabilitation*. 1999; 78(4):354–360. [PubMed: 10418842]
- Kim CM, Eng JJ. Magnitude and pattern of 3D kinematic and kinetic gait profiles in persons with stroke: relationship to walking speed. *Gait and Posture*. 2004; 20(2):140–146. [PubMed: 15336283]
- Lamontagne A, et al. Mechanisms of disturbed motor control in ankle weakness during gait after stroke. *Gait and Posture*. 2002; 15(3):244–255. [PubMed: 11983499]
- Lin P-Y, et al. The relation between ankle impairments and gait velocity and symmetry in people with stroke. *Archives of Physical Medicine and Rehabilitation*. 2006; 87(4):562–568. [PubMed: 16571398]

- Lusardi, M.; Jorge, M.; Nielsen, C. *Orthotics and Prosthetics in Rehabilitation*. 3rd ed.. St. Louis, MO: Elsevier Saunders; 2013.
- Mayo NE, et al. Disablement following stroke. *Disability and Rehabilitation*. 1999; 21(5–6):258–268. [PubMed: 10381238]
- Murray MP, et al. Treadmill vs. floor walking: kinematics, electromyogram, and heart rate. *J Appl Physiol*. 1985; 59(1):87–91. [PubMed: 4030579]
- Olney SJ, et al. Work and power in gait of stroke patients. - Abstract - UK PubMed Central. *Archives of Physical Medicine and Rehabilitation*. 1991; 72(5):309–314. [PubMed: 2009047]
- Olney SJ, Griffin MP, McBride ID. Temporal, kinematic, and kinetic variables related to gait speed in subjects with hemiplegia: a regression approach. *Physical therapy*. 1994; 74(9):872–885. [PubMed: 8066114]
- Perry J, et al. Classification of Walking Handicap in the Stroke Population. *Stroke*. 1995; 26(6):982–989. [PubMed: 7762050]
- Perry, J. *Gait Analysis: Normal and Pathological Function*. 1st ed.. Thorofare, NJ: STACK Incorporation; 1992.
- Riley PO, et al. A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. *Gait and Posture*. 2007; 26(1):17–24. [PubMed: 16905322]
- Schmid A, et al. Improvements in speed-based gait classifications are meaningful. *Stroke*. 2007; 38(7): 2096–2100. [PubMed: 17510461]
- Titianova EB, Tarkka IM. Asymmetry in walking performance and postural sway in patients with chronic unilateral cerebral infarction. *Journal of Rehabilitation Research and Development*. 1995; 32(3):236–244. [PubMed: 8592295]

Figure 1.

Average peak joint angles during swing phase of the paretic limb across all self-selected walking speeds for (a) ankle dorsiflexion, (b) knee flexion, (c) pelvic tilt, and (d) hip abduction. Vertical lines at 0.4 and 0.8 m/s represent speed divisions between ambulation categories determined by Perry et al.

Table 1

Averages (standard deviations) of participant demographics by ambulation category.

	Household	Limited Community	Community
Participants	N=8 (2F, 6M)	N=7 (2F, 5M)	N=6 (0F, 6M)
Age (years)	63.6 (11.9)	64.3 (9.5)	54.9 (8.3)
BMI (kg/m ²)	30.6 (5.8)	28.8 (6.0)	33.2 (5.9)
Side of paresis (L/R)	5/3	5/2	4/2
Months since stroke	87.9 (91)	55.7 (51.6)	39.6 (39.4)
Self-selected walking speed (m/s)	0.26 (0.05)	0.59 (0.15)	1.04 (0.08)
Fugl-Meyer Lower Extremity* (Max 34)	19 (5.6)	22 (6.9)	25 (2.1)

* (Fugl-Meyer et al., 1975)

Table 2

Ambulation category medians (range) for paretic joint angles and toe displacement during swing.

	Household	Limited Community	Community
Peak Ankle Dorsiflexion (°)	8.2 (1.8–16.4)	15.3 (5.9–19.2)	18.7 (12.6–26.3)
Peak Knee Flexion (°)	23.0 (10.6–40.7)	46.6 (35.1–63.2) ⁺	51.3 (40.0–60.4) ⁺
Peak Pelvic Tilt (°)	8.3 (4.0–13.6)	4.7 (2.9–11.0)	2.0 (1.0–5.4) ⁺
Peak Hip Abduction (°)	3.4 (0.9–5.8)	4.9 (0.6–7.9)	9.7 (0.7–20.2)
Toe Displacement (m)	0.022 (0.032)	0.034 (0.021)	0.021 (0.013)

⁺ Denotes significant differences compared to Household ambulator category