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**Article Title:** The Relationship Between Spatiotemporal Gait Asymmetry and Balance in Individuals With Chronic Stroke

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The relationship between spatiotemporal gait asymmetry and balance in individuals with chronic stroke

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Running Title: Gait and balance post-stroke
Abstract

Falls are common after stroke and often attributed to poor balance. Falls often occur during walking, suggesting that walking patterns may induce a loss of balance. Gait after stroke is frequently spatiotemporally asymmetric, which may decrease balance. The purpose of this study is to determine the relationship between spatiotemporal gait asymmetry and balance control. Thirty-nine individuals with chronic stroke walked at comfortable and fast speeds to calculate asymmetry ratios for step length, stance time, and swing time. Balance measures included the Berg Balance Scale, step width during gait, and the weight distribution between legs during standing. Correlational analyses determined the relationships between balance and gait asymmetry. At comfortable and fast gait speeds, step width was correlated with stance time and swing time asymmetries (r=0.39–0.54). Berg scores were correlated with step length and swing time asymmetries (r=-0.36–0.63). During fast walking, the weight distribution between limbs was correlated with stance time asymmetry (r=-0.41). Spatiotemporal gait asymmetry was more closely related to balance measures involving dynamic tasks than static tasks, suggesting that gait asymmetry may be related to the high number of falls post-stroke. Further study to determine if rehabilitation that improves gait asymmetry has a similar influence on balance is warranted.

Keywords: stroke, gait, spatiotemporal asymmetry, balance, rehabilitation

Word Count: 3964 (including references)
Introduction

Approximately 45-73% of individuals following stroke experience a fall in the 6 months after discharge from rehabilitation. These falls can cause additional injury, prolong the rehabilitation process, have detrimental psychological effects, and add additional costs. Although the cause of falls is multifactorial, balance/postural control is frequently impaired following stroke and represents one of the largest contributing factors to falls in this population. Because falls suffered by community dwelling individuals following stroke occur most often during walking, it has been suggested that the walking pattern may induce a loss of balance. Importantly, both gait deviations and balance deficits are associated with similar impairments (e.g., hemiparesis, altered sensory function, and/or lack of confidence in the paretic limb), although the relationship between gait patterns and balance has not yet been established.

Both quiet stance and gait following stroke are characterized by marked asymmetry. During quiet stance, there is greater weight bearing through the non-paretic leg compared to the paretic side. This tendency to maintain the COM towards the non-paretic limb is also observed during gait and requires the non-paretic swing phase to be cut short, with the non-paretic stance phase beginning more quickly to prevent a fall. Concurrently, the shortened non-paretic swing phase often results in a shortened non-paretic step length. The resulting spatiotemporal gait asymmetries (i.e., stance time, swing time, and step length asymmetries) are well documented in many individuals post-stroke, and have been purported to be related to impairments in balance. Although it is currently unknown if spatiotemporal gait asymmetries are, in fact, related to impairments in balance, this question has important clinical implications for the large number of individuals who walk with gait asymmetry following stroke.
The purpose of this study is to determine the presence of a relationship between spatiotemporal gait asymmetry and measures of balance during both static and dynamic tasks. Given the similar mechanisms underlying spatiotemporal gait asymmetry and diminished balance (e.g., hemiparesis, sensorimotor dysfunction), it is hypothesized that both spatial and temporal gait asymmetries will be related to balance measures during static and dynamic tasks.

**Methods**

We recruited 39 individuals (23 M / 16 F; age: 56.7 ±10.5 years; height: 1.72 ± 0.10 m; weight: 87.5 ± 10.2 kg) with chronic stroke. All subjects exhibited clinical symptoms consistent with lower extremity hemiparesis from an ischemic or hemorrhagic unilateral brain lesion that occurred more than six months prior to testing. Potential participants were excluded if they had a cerebellar lesion, any concurrent neurologic condition that could affect walking ability (e.g., Parkinson’s disease), a history of balance deficits or unexplained falls that predated the stroke, or impaired cognition that affected the ability to follow directions. Potential participants were included if they could stand unsupported without an assistive device and be able to walk 10 m without therapist assistance. Although participants used their typical shoes, ankle foot orthotic (AFO), and assistive devices (e.g., canes), no therapist assistance was provided. The time since stroke was 54 ± 60 months and the lower extremity portion of the Fugl-Meyer was 24.8 ± 4.4. Twenty-two of the participants experienced hemiparesis on the right side. All participants signed an informed consent form approved by the University of North Carolina at Chapel Hill prior to participation.

All testing occurred during a single session and consisted of both an overground gait assessment and balance testing. Overground gait was assessed by having participants walk across a 4.27 m (14 foot) GAITRite mat (CIR Systems, Havertown, PA). Approximately 1 – 1.5
m (3-5 feet) was provided for acceleration and deceleration, which was not collected. Each participant completed three passes at a self-selected, comfortable gait speed (CGS), and three additional passes at a fast gait speed (FGS). Participants were verbally encouraged to walk “as fast as they felt safe”, during FGS trials. We tested both CGS and FGS because of the different implications for diminished balance at each speed. For instance, people spend the majority of the time walking at CGS, suggesting that there are greater opportunities to fall at this speed. During FGS, however, it is presumed that the additional gait velocity may require greater control of the resulting inertia and collisional forces imposed by the faster limb movements. Additionally, external factors that require the need for greater gait speed (a medical emergency or other panicked situation) may further increase the risk for falls.

Balance was assessed with the Berg Balance Scale (BBS),\textsuperscript{19} which has been shown to be a valid and reliable assessment of balance for individuals with chronic stroke.\textsuperscript{20} Notably, the BBS has been used to establish cut-off scores (i.e., 49-52) which are indicative of fall risk in individuals post-stroke,\textsuperscript{21,22} although the use of the BBS as a dichotomous measure has been discouraged due to reduced sensitivity of the measure.\textsuperscript{23} Balance was also measured as the weight distribution between limbs during quiet stance. This measure is important because weight bearing during quiet stance is typically asymmetrical following stroke,\textsuperscript{9,10,13,14} and during gait the weight distribution between limbs has been related to temporal asymmetry.\textsuperscript{17} Assessment of weight distribution between limbs was performed with participants standing with the feet at shoulder-width, such that each foot was on a different force plate (Bertec Corp, Columbus, OH). Subjects stood for approximately one minute while a Vicon motion capture system sampled one second of ground reaction force data from both force plates at 960 Hz. We acknowledge that one second of collection is substantially shorter than what has been described
previously,

although we feel that this time frame provides sufficient data to make the weight assessment. The final assessment of balance was step width during comfortable and fast gait speeds, as measured during the overground gait assessment described above. Although not considered a traditional measure of balance performance, step width is known to be greater in individuals post-stroke,

has been related to falls and fear of falling in elderly individuals,

and has been related to other, more traditional, measures of balance and gait stability.

Data Analysis

After data collections, GAITRite software calculated step length, step width, stance time and swing times of each step. We analyzed a total of 22 ± 7 steps for CGS and 19 ± 8 steps for FGS. Symmetry ratios were created between the non-paretic and paretic limbs for step length, stance time, and swing time. All ratios were inverted, if necessary, such that values were greater or equal to one. Therefore a value of 1.00 represents perfect symmetry for a given variable with larger values indicating greater asymmetry. Previous work has suggested that ratios that exceed 1.08 for step length asymmetry, 1.05 for stance time asymmetry, and 1.06 for swing time asymmetry are considered significantly different than healthy controls. Step width was calculated as the medial/lateral distance between the respective stance phases of two consecutive steps. Step width was calculated for all steps along each pass of the GaitRite mat and averaged to devise an average step width. Weight distribution through the paretic limb (%Par) was derived from the vertical ground reaction forces and calculated as:

\[ \%\text{Par} = \frac{VGRF_{\text{par}}}{VGRF_{\text{par}} + VGRF_{\text{npar}}} \times 100\% \]

where \( VGRF_{\text{par}} \) and \( VGRF_{\text{npar}} \) are the average vertical ground reaction force over the one second of recorded data for the paretic and non-paretic limbs, respectively.
Statistical Analysis

All statistical analyses were performed with SPSS (ver. 16, Chicago, IL). The relationship between CGS and spatiotemporal asymmetry was first determined using Pearson correlations. Measures of balance were then related to gait asymmetry ratios and gait speed using Pearson correlations (step width and %Par) or Spearman rank correlation (Berg Balance Scale). Separate correlations were calculated for both comfortable (CGS) and fast (FGS) gait speeds for each pair of balance and asymmetry measure. For the correlations between step width and each of the gait symmetry ratios, gait velocity was designated as a covariate to account for differences in step width due to difference in gait speed.

Results

The average gait speed during CGS was 0.65 ± 0.27 m·s⁻¹ (range: 0.16 – 1.15 m·s⁻¹) and average speed during FGS was 0.88 ± 0.42 m·s⁻¹ (range: 0.19 – 1.76 m·s⁻¹). At the comfortable gait speed, step length asymmetry averaged 1.26 ± 0.37, stance time asymmetry was 1.16 ± 0.12, and swing time asymmetry was 1.45 ± 0.44. Twenty four of the participants (62%) exceeded the threshold of 1.08 that defines asymmetry in step length, thirty one of the participants (79%) exceeded the threshold of 1.05 that defines asymmetry in stance time, and thirty two participants (82%) exceeded a threshold of 1.06 to define swing time asymmetry. Comfortable gait speed was significantly related to step length (r = -.55; p < .001), stance time (r = -.41; p = .010), and swing time (r = -.57; p < .001) asymmetry ratios. Asymmetry ratios at the fast walking speed were 1.23 ± 0.36 (step length), 1.38 ± 0.36 (swing time), and 1.15 ± 0.12 (stance time). The average Berg Balance Scale score was 48 ± 6 (range: 26-56), the average weight borne through the paretic limb was 45 ± 8%BW, and the average step width was 16.9 ± 5.6 cm at CGS and 16.8
± 6.1 cm at FGS. No difference in step width between CGS and FGS walking conditions was observed (p = .939).

While walking at comfortable, self-selected gait speed, correlation coefficients indicated several significant relationships between measures of spatiotemporal gait asymmetry and balance measures (see Table 1). The Berg Balance Scale was negatively correlated with both step length asymmetry (r = -.61; p < .001) and swing time asymmetry (r = -.36; p = .025) (Figure 1). Step width during gait was positively correlated with stance time asymmetry (r = .39; p = .015), and swing time asymmetry (r = .42; p < .001) after accounting for gait velocity (Figure 2). The weight distribution between limbs was not correlated with any of the gait asymmetry ratios (all p > .084). Comfortable gait speed was significantly related to %Par (r = .38, p = .016), the Berg Balance Scale (r = .79, p < .001), and step width (r = -.60, p < .001).

During fast walking, the Berg Balance Scale was negatively correlated with both step length asymmetry (r = -.63; p < .001) and swing time asymmetry (r = -.44; p = .005). Step width during FGS was positively correlated with both stance time asymmetry (r = .45; p = .005) and swing time asymmetry (r = .54; p < .001) using gait speed as a covariate. Finally, the weight distribution between limbs was negatively correlated with stance time asymmetry at FGS (r = -.41; p = .010). Fast gait speed was significantly related to %Par (r = .39, p = .013), the Berg Balance score (r = .80, p < .001), and step width during FGS (r = -.47, p = .003).

**Discussion**

Our hypothesis that spatiotemporal gait asymmetries would be related to impairments in balance during static and dynamic tasks in people with chronic stroke was supported. Specifically, during CGS, stance time and swing time asymmetry ratios were positively correlated with step width during gait, whereas swing time and step length asymmetry ratios
were negatively correlated with the BBS. In all relationships greater spatiotemporal asymmetry was related to greater impairments in balance (i.e., lower BBS score or larger step width). Notably, we observed a greater number of significant relationships between gait asymmetry ratios and balance measures that involved dynamic tasks (i.e., BBS, step width), than the balance measure involving only a static task (%Par). Given the importance of balance to minimize falls and the fact that many falls occur while walking, it is possible that the presence of spatiotemporal gait asymmetry is related to the high number of falls post-stroke.

Measures of balance were correlated with both spatial and temporal measures of gait asymmetry. Interestingly, however, stance and swing time asymmetry ratios were not related in the same way to the various balance measures (e.g., only SwTA was related to the BBS), suggesting that these two temporal measures represent different requirements by the neuromusculoskeletal system. Stance time incorporates two double support periods, which may provide stability, whereas the swing time is the equivalent of single limb support for the contralateral limb. That the BBS was significantly correlated with swing time asymmetry (no double support times) and not stance time asymmetry ratios suggests that swing time asymmetry may be more important as a marker for diminished balance.

Our data showed comparable relationships between balance and spatiotemporal asymmetry ratios at the two tested gait speeds. Step width, in particular, did not change as subjects transitioned from CGS to FGS. This is important because step width becomes smaller as gait speed is increased in unimpaired individuals. This was observed between our subjects, such that the slower walkers exhibited larger step widths. The wider step width during gait is thought to reflect a compensation to improve balance during gait. That slower walkers chose
wider step widths at both CGS and FGS, suggests that the slower walkers may feel more unsteady regardless of their chosen walking speed (e.g., CGS or FGS).

We were surprised that the weight distribution between limbs during quiet stance didn’t correlate with any of the spatiotemporal measures at CGS. Others have previously demonstrated relationships between weight distribution during gait and various spatiotemporal gait asymmetries. Balasubramanian and colleagues (2010) suggested that taking a wider step with the paretic limb, compared to the non-paretic, was associated with an uneven weight distribution during gait. In contrast, our weight distribution measure was obtained during quiet standing. The lack of an observed relationship between spatiotemporal gait asymmetry and quiet standing weight distribution may be related to the different task requirements of standing and gait. In support of our findings, prior work has established that practice to improve weight distribution during quiet standing does not transfer to improvements in gait. It is possible that requiring participants in our study to stand with feet at shoulder width improved the weight distribution between limbs. Likewise, the allowance of AFOs, if necessary, during quiet standing may have provided support to the paretic ankle, allowing greater load through the paretic limb. We chose to allow participants to use their AFO during testing, since that was what they would routinely use throughout the day and would give a better indication of home and community functioning level. Nevertheless, the average weight through the paretic legs of our participants was only slightly greater than what has been reported by others.

This study used measures of balance that included both static and dynamic tasks. Specifically, step width during gait is believed to represent balance control during a dynamic activity, the Berg Balance Scale contains measures of both static and dynamic balance, and the weight distribution between limbs represents balance during a static task. Given that gait is a
dynamic activity that requires adequate balance control to avoid falling, it is not surprising that the measures of balance that incorporated dynamic tasks were related to spatiotemporal gait asymmetry ratios, while the balance measures during quiet standing were not.

Although we observed significant relationships between spatiotemporal asymmetry ratios and our measures of balance performance (i.e., BBS and step width), many of these correlations are considered ‘weak to moderate’ relationships. It is possible, however, that the relationships are weak at lower spatiotemporal asymmetry values until the asymmetries get larger. The established thresholds\(^{11}\) that were used for classifying the presence of spatiotemporal asymmetry may be appropriate for those needs, but not for establishing ‘fall risk/balance deficits’.

Significant relationships between gait parameters and measures of balance performance have been previously documented. Although we are unaware of other work that links spatiotemporal gait asymmetry with balance measures, the use of deep brain stimulation (DBS) can improve both asymmetric gait patterns\(^{34}\) and postural sway measures\(^{35}\) in individuals with Parkinson’s disease. Others have shown significant relationships between other measures of gait and balance. In particular, gait speed has previously been associated with the BBS in individuals post-stroke.\(^{20}\) In addition, elderly fallers exhibit gait strategies that are different than non-fallers.\(^{26}\) For instance, step width is known to be wider, and gait velocity is slower in those who are fallers.\(^{26}\) Although a direct linkage between spatiotemporal gait asymmetry and balance deficits has not yet been made, these studies provide indirect evidence in support of our conclusions.

There are several important limitations to this research study. First, it is important to recognize that correlations are not indicative of cause and effect, and can only identify relationships between variables. It is therefore unclear if improving spatiotemporal symmetry
will improve balance and reduce fall risk. A longitudinal study documenting changes in spatiotemporal symmetry and changes in balance and number of falls would be required to support this assertion. It is also important to note that we intentionally included subjects with and without spatiotemporal asymmetry. Increasing the range of spatiotemporal symmetry ratios, rather than restricting the analysis to only those with asymmetry, may have affected our correlation coefficients. Increasing the range of symmetry ratios, however, makes our results more applicable to a larger sample of individuals post-stroke. Finally, both spatiotemporal gait asymmetry and balance have been related to similar underlying impairments (e.g., muscle weakness, \textsuperscript{36} spasticity, \textsuperscript{8,36} decreased sensory function, \textsuperscript{8} balance confidence\textsuperscript{37}), suggesting that it is possible that a common underlying mechanism is influencing our observed relationship. Unfortunately, we did not measure these potential confounding variables, and thus feel that this is an important area for future work.

In conclusion, we observed a significant relationship between spatiotemporal gait asymmetries and measures of balance. Notably, the measures of balance that were related to gait asymmetry involved dynamic tasks, rather than static tasks. Further exploration will be necessary to determine if changing spatiotemporal asymmetry in patients with chronic stroke has a concomitant beneficial impact on balance.
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Figure 1: A significant negative relationship was observed between Berg Balance Scale scores and (A) swing time asymmetry ratios ($r = -.358; p = .025$) and (B) step length asymmetry ratios ($r = -.614; p < .001$) during comfortable gait speed. BBS = Berg Balance Scale; SwTA = swing time asymmetry ratio; SLA = step length asymmetry ratio.
Figure 2: A significant positive relationship was observed between step width at comfortable gait speed and (A) stance time asymmetry ratios (r = .421; p = .009) and (B) swing time asymmetry ratio (r = .393; p = .015). STA = stance time asymmetry ratio; SwTA = swing time asymmetry ratio.
Table 1. Correlations between measures of balance and of spatiotemporal gait asymmetry ratios

<table>
<thead>
<tr>
<th>Correlation between</th>
<th>Comfortable Gait Speed (CGS)</th>
<th>Fast Gait Speed (FGS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBS and STA</td>
<td>r = -.280; p = .203</td>
<td>r = -.281; p = .083</td>
</tr>
<tr>
<td>BBS and SwTA</td>
<td>r = -.358; p = .025</td>
<td>r = -.437; p = .005</td>
</tr>
<tr>
<td>BBS and SLA</td>
<td>r = -.614; p &lt; .001</td>
<td>r = -.631; p &lt; .001</td>
</tr>
<tr>
<td>%Par and STA</td>
<td>r = -.280; p = .084</td>
<td>r = -.405; p = .010</td>
</tr>
<tr>
<td>%Par and SwTA</td>
<td>r = -.198; p = .227</td>
<td>r = -.252; p = .122</td>
</tr>
<tr>
<td>%Par and SLA</td>
<td>r = -.218; p = .182</td>
<td>r = -.195; p = .234</td>
</tr>
<tr>
<td>SW and STA</td>
<td>r = .421; p = .009</td>
<td>r = .447; p = .005</td>
</tr>
<tr>
<td>SW and SwTA</td>
<td>r = .393; p = .015</td>
<td>r = .543; p &lt; .001</td>
</tr>
<tr>
<td>SW and SLA</td>
<td>r = .056; p = .737</td>
<td>r = .107; p = .521</td>
</tr>
</tbody>
</table>

Shaded cells indicate significant relationship (p<0.05).

BBS: Berg Balance Scale; %Par: percent of weight born through the paretic limb during quiet unsupported stance; SW: step width during gait; STA: Stance Time Asymmetry; SwTA: Swing Time Asymmetry; SLA: Step Length Asymmetry.