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Symmetry in vertical ground reaction force is accompanied by symmetry in temporal but not distance variables of gait in persons with stroke

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Abstract

The purpose of this study was to (1) determine whether symmetry in temporal-distance (T-D) measures is accompanied by symmetry in kinetic measures during self-paced gait and (2) evaluate the effect of symmetry on gait speed in individuals with chronic stroke. A symmetry index was calculated for stance time, swing time, step length and vertical ground reaction force (GRF) for 28 individuals with stroke (age: 62.5 ± 8.2 years). Spearman correlation revealed that (a) gait speed was correlated with the symmetry of temporal measures and GRF and (b) symmetry in GRF was correlated with symmetry in temporal but not distance measures of gait ($P < 0.05$). The results provide support for promoting temporal and kinetic symmetry in the gait of persons with stroke.

Keywords: Ground reaction force; Symmetry; Gait analysis; Stroke

1. Introduction

In healthy individuals, gait patterns with respect to time, distance and vertical force are fairly symmetrical deviating by only a small percentage from perfect symmetry. For example, the difference between the two lower limbs calculated using a symmetry index [1] for temporal measures and vertical force were reported to be less than 6% in able-bodied gait [2–4]. In pathological gait, however, marked asymmetry has been noted between the affected and unaffected lower limbs. Shorter stance time, prolonged swing time and decreased ground reaction forces (GRFs) have been reported on the affected limb relative to the unaffected limb in the gait of persons with stroke, osteoarthritis, and in persons with prosthetic limbs [4–9].

Does the degree of gait asymmetry relate to measures of motor recovery and function in persons with stroke? Brandstater et al. [10] found that symmetry of swing time was related to the stage of motor recovery and gait speed in a group of persons with acute stroke. Similarly, Titianova and Tarkka [4] also found a significant relationship between the symmetry for swing time and gait speed in a group of chronic stroke survivors. In contrast, other studies have found this relationship to be non-significant in persons with chronic stroke [11–13]. Nonetheless, despite the contrasting results, studies continue to use temporal-distance (T-D) symmetry as an indicator of gait performance and a measure for evaluating intervention strategies [14–16].

Although T-D symmetry is commonly analyzed, the symmetry in kinetic measures is rarely examined in persons with stroke. Kinetic variables (e.g. force) may be considered more informative since they provide insight into the cause, rather than the effect, of the movement [17,18]. One study [7] has analyzed the relationship between symmetry of the impulse of GRF and gait speed in persons with stroke and found a significant correlation, thereby concluding that GRF well reflects gait ability in these individuals.

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In addition, it is not known how T-D symmetry relates to the symmetry of kinetic variables (e.g. GRF) during gait. Therefore, the purpose of this study was to determine whether symmetry in T-D measures (stance time, swing time, and step length) is accompanied by symmetry in GRF measures during gait and in addition, quantify the relationship between the symmetry of these variables and gait speed in a group of individuals with chronic stroke.

2. Methods

2.1. Subjects

Twenty-eight individuals with hemiparesis caused by a single cerebrovascular accident volunteered to participate in the study. Inclusion criteria for this study were: (1) at least 6 months post stroke, (2) age 50 or over, and (3) able to ambulate independently without an assistive device. Subjects who had orthopaedic or neurological conditions in addition to the stroke were excluded from the study. Ethics approval was obtained from the university and local hospital ethics committees. Each subject was informed of the study procedures before giving their consent to participate in the study. Each subject's impairment level for the leg and foot was evaluated using the Chedoke–McMaster Stroke Assessment recovery stages.

2.2. Procedures

Subjects were asked to walk wearing their shoes at their 'most comfortable speed' (i.e. self-selected speed) along an 8 m walkway over three force plates (Bertec, Columbus, OH) used to record GRFs. After each walking trial, the starting position of the subjects was adjusted to maximize the number of steps landing on force plates. The instructions were 'walk as you normally would until you reach the end line'. If a subject appeared to adjust their step during the walking trial to target a force plate, clear explanations were provided to the subjects regarding the importance of walking in their usual manner during the tests and avoid targeting the force plates. Five 'appropriate' trials were collected for each limb. A trial was considered 'appropriate' if only one foot landed on a force plate and in its entirety. This was determined through visual observation by an assistant standing on a platform three feet away from the force plates as well as with video recording. When necessary, rest breaks were taken between trials to ensure that participants were not fatigued and the trial reflected their true self-selected speed.

An optoelectronic sensor (Nothern Digital, Waterloo, Canada) with three calibrated position sensors was used to track the three-dimensional coordinates of infrared light emitting diodes (IREDs) attached to the participants' lateral malleoli. In this camera set-up, the error of locating the coordinates of an IRED in space was 0.9 mm in the anterior/posterior direction and 0.45 mm in the up/down direction. IREDs and force plate data were synchronized and sampled at 60 and 600 Hz, respectively, and then filtered using a second-order Butterworth, low-pass filter at 6 and 50 Hz, respectively.

The time of initial foot contact was identified by the rise (>5 N) in vertical GRF while the position was measured by the lateral malleolus marker at the corresponding time. Similarly, the end of foot contact was identified when the vertical GRF returned to within 5 N. Gait speed was then calculated using the cumulative consecutive stride lengths (forward distance covered by the lateral malleolus marker from initial foot contact to the next initial foot contact of the same leg) in the middle 4 m section (i.e. representative window of constant gait speed) of the 8 m walkway and the corresponding elapsed time. Step length was measured using the forward distance covered by foot contact of one leg to the following foot contact of the other leg (Fig. 1a). Stance and swing times were also extracted using both IRED and force plate data (Fig. 1b). Force plate variable of interest was the average magnitude of the vertical GRF over the stance phase of gait (Fig. 1c).

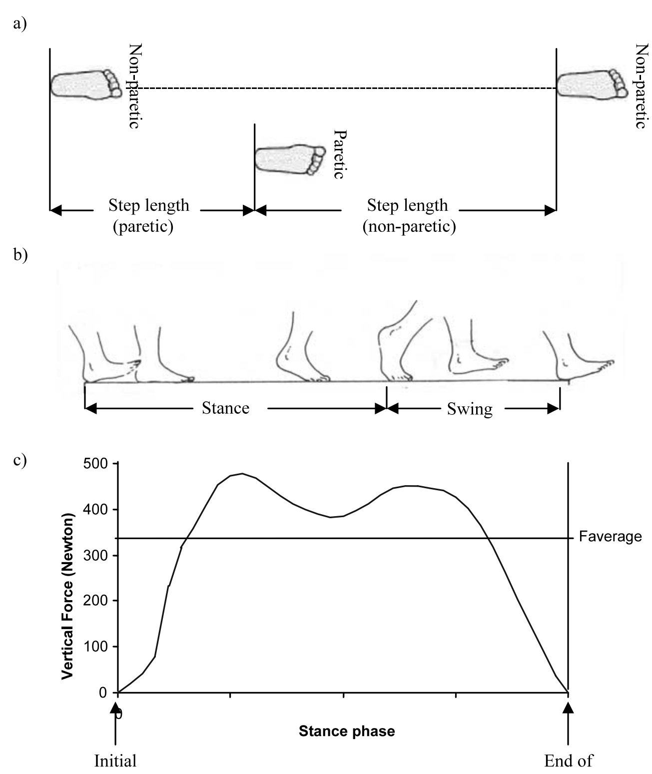

Fig. 1. Visualization of (a) paretic and non-paretic step length, (b) temporal variables, and (c) average magnitude of the vertical GRF over the stance phase of gait (Faverage).

2.3. Data analysis

Descriptive statistics were performed for all variables measured. To account for possible effects due to anthropometrics (e.g. leg length), gait speed was normalized to leg length and expressed in units per second. For each T-D and force plate variable (Vi), a symmetry index (SI) proposed by Robinson et al. [1] was used to quantify asymmetries in gait:

$$SI = \frac{V_{paretic} - V_{nonparetic}}{1/2(V_{paretic} + V_{nonparetic})} \times 100$$

where $V_{paretic}$ is a gait variable recorded for the paretic limb and $V_{nonparetic}$ is the corresponding variable for the nonparetic limb. The magnitude of SI represents the degree of asymmetry and the sign indicates the pattern of asymmetry. A symmetry index value of zero represents perfect symmetry. Note that the degree of asymmetry could range from −200 to 200% as the difference between the two sides is reported against their average value. A positive (+ve) SI indicates that the magnitude of that variable was larger on the paretic limb, while a negative (−ve) sign denotes a larger magnitude on the non-paretic limb. Symmetry indices were described as SI_{stance}, SI_{swing}, SI_{step}, and SI_{GRF} for stance time, swing time, step length, and vertical GRF variables, respectively.

The SI for each variable (expressed in absolute values) was correlated with gait speed (normalized to leg length) across subjects using Spearman correlation at a significance level of 0.05 (two-tailed) in order to determine whether the degree of asymmetry in T-D and GRF measures related to gait speed. Spearman correlation was also performed to determine the relationship between T-D symmetry and GRF symmetry (using absolute values). All statistical analyses were performed with SPSS 9.0 software.

3. Results

Subject characteristics and mean values of all gait measures including the symmetry indices are presented in Tables 1 and 2, respectively. The coefficient of variation (CV) across the five trials for the T-D and GRF measures was low. The CV for stance time was 5 ± 3% (across the 28 subjects for the paretic and nonparetic limbs), for swing time 7 ± 4%, for step length 6 ± 4%, and for vertical GRF 3 ± 1%. All subjects were able to walk without walking aids, however, five subjects required the use of an ankle foot orthosis to walk.

Table 1
Subject characteristics ($N = 28$)

Variable	Mean	Standard Deviation	Range
Age (years)	62.5	8.2	50–82
Time since stroke (years)	4.4	2.8	1–11
Type of stroke			
Hemorrhagic	10		
Ischemic	15		
Unspecified	3		
Height (m)	1.68	0.12	1.43–1.85
Leg length (m)	0.76	0.07	0.61–0.88
Weight (kg)	77.8	15.6	45.2–113.9
Sex (M/F)			20/8
Affected side (R/L)			14/14
Chedoke–McMaster[a] (stage range)			2–7

[a] Recovery stage level on the Chedoke–McMaster Stroke Assessment [19] for the paretic foot and leg, minimum stage = 1 and maximum stage = 7.

Table 2
T-D gait variables, GRF and symmetry indices for the subject population ($N = 28$)

Variable		Mean	Standard deviation
Gait speed (m/s)		0.81	0.28
Stance time (s)	Paretic side	0.79	0.20
	Nonparetic side	0.89	0.25
Swing time (s)	Paretic side	0.49	0.11
	Nonparetic side	0.37	0.07
Step length (mm)	Paretic side	475.5	130.3
	Nonparetic side	484.8	113.5
Vertical GRF (N)	Paretic side	537.1	122.5
	Nonparetic side	605.1	131.0
SI_{stance}		13.6	9.1
SI_{swing}		27.3	19.8
SI_{step} (all)[a]		17.3	18.0
SI_{step} (+ve)[a]		13.7	14.7
SI_{step} (−ve)[a]		20.8	20.8
SI_{GRF}		12.8	9.5

All SI values entered in absolute values. Abbreviations: symmetry index (SI), ground reaction force (GRF).
[a] SI_{step} for all subjects (all, $N = 28$), for subjects with greater step length on the paretic side only (+ve, $N = 14$), and for subjects with greater step length on the nonparetic side only (−ve, $N = 14$).

3.1. T-D and vertical GRF symmetry indices

The pattern of asymmetry for swing time (+ve), stance time (−ve) and vertical GRF (−ve) were consistent across subjects except for one, two and three subjects, respectively. That is, swing time was relatively longer for the paretic limb and stance time longer for the nonparetic limb along with a greater GRF on that side. However, the pattern of asymmetry for step length was more variable (positive for 14 subjects and negative for the other 14 subjects) indicating that half of the subjects took a longer step on their paretic side while the other half demonstrated the opposite pattern. Note that although half of the subjects in this study were affected on the same side post-stroke, further observation of the data revealed no relationship between the sign of SI_{step} (i.e. pattern of asymmetry) and side affected by the stroke. Marked asymmetry was noted for all variables (Table 2). The mean magnitude of SI was highest for swing time and lowest for the vertical GRF.

3.2. Correlations

Results of the correlational analyses showed a significant correlation between SI's and gait speed for all variables measured except for SI_{step} and the highest correlation coefficient was found with SI_{GRF} (Table 3). Similarly, SI_{GRF} was significantly correlated with the degree of asymmetry in temporal measures but not with the degree of asymmetry in step length. Of note, a secondary analysis was also undertaken for all correlations involving SI_{step}, as the pattern of asymmetry for this variable was inconsistent across subjects (larger on the paretic side for 14 subjects and larger on the nonparetic side for the other 14 subjects). Consequently, correlational analyses involving SI_{step} were performed in three subgroups: (1) for all subjects using absolute values of SI_{step} ($N = 28$), (2) for subjects exhibiting a larger step length on the paretic side only ($N = 14$), and (3) for subjects exhibiting a larger step length on the nonparetic side only ($N = 14$).

Table 3
Spearman correlation between gait speed and symmetry indices ($N = 28$)

	Gait speed (normalized to leg length)	SI_{GRF}
SI_{GRF}	−0.686**	
SI_{stance}	−0.429*	0.586**
SI_{swing}	−0.567**	0.678**
SI_{step} (all)[a]	−0.321	0.212
SI_{step} (+ve)[a]($N = 14$)	−0.226	0.358
SI_{step} (−ve)[a]($N = 14$)	−0.486	0.081

*, Significant at $P < 0.05$; **, significant at $P < 0.01$. Abbreviations: symmetry index (SI), ground reaction force (GRF).

[a] Correlations with SI_{step}: all subjects (all), subjects with longer step on the paretic limb only (+ve), and subjects with longer step on the non-paretic limb only (−ve).

4. Discussion

4.1. Degree and pattern of gait asymmetry

The subjects that participated in this study presented a wide range of functional levels as was evident by their stage level on the Chedoke–McMaster Stroke Assessment [19] (range 2–7) and the range in gait speed (0.34–1.42 m/s). The mean symmetry indices deviated considerably from zero (i.e. perfect symmetry). The magnitudes of the symmetry indices found in this study were similar in range with findings previously reported by others [4] using the same symmetry index for temporal gait measures (i.e. stance time and swing time). The degree of asymmetry was relatively greater for swing time than for other variables. However, one must be cautious in this interpretation as variables that have large values (e.g. GRF) will tend to lower the SI and vice versa.

The pattern of asymmetry for temporal measures and vertical GRF observed in this study has been also described by others [7,9,12,20,21]. Except for one to three subjects, there was a tendency for a prolonged swing, a shorter stance period, and a reduction in GRF on the paretic limb, possibly caused by muscle weakness and balance deficiencies on that side. For step length, however, the pattern was more variable. Contrary to previous studies that showed a trend for greater step length on the paretic side compared with the nonparetic side, [9,21] half of the subjects in this study exhibited the opposite pattern. The discrepancy in findings may be due to differences in sample size and/or differences in subject population (e.g. duration of injury). For example, Wall and Ashburn [9] included only a small number of subjects in their study ($N = 5$) and Mizrahi et al. [21] studied a group of acute stroke survivors (mean duration of stroke = 3.4 months). A chronic group such as the subjects in this study may present with more variable patterns as a result of various compensatory strategies developed since their stroke.

4.2. Gait speed, T-D measures, and vertical GRF

The degree of asymmetry in temporal measures and vertical GRF during gait was found to be associated with gait performance as measured by gait speed. In agreement with our results, previous studies have also found that the degree of asymmetry in swing time and vertical force was related to gait performance [4,7,10,22]. The level of association found in this study for SI_{swing} ($r = -0.57$) was similar to that reported by Titianova and Tarkka [4] where asymmetry was quantified using the same method. However, in contrast to our findings, others [12,13,23] have reported only weak ($r = 0.41$) or no significant relationship ($P > 0.05$) between T-D symmetry and gait performance. These contrasting findings may be due to the inclusion of subjects walking with a walking aid in previous studies, [12,13,23] which may have altered the degree and pattern of asymmetry between the two lower limbs. Walking aids were reported to have a significant effect on swing time symmetry in twenty percent of a study cohort of individuals with stroke [12]. In addition, except for Wall and Turnbull, [13] differences in anthropometrics between subjects were not accounted for when measuring gait speed [12,23]. A relative measure of gait speed which is normalized to body height or leg length has been shown to better relate to other gait variables since inter-individual variability of stature and leg length is factored out [24].

Among the variables tested, the highest correlation with speed was found with SI_{GRF} followed closely by SI_{swing}. The significant correlation between the GRF symmetry and gait speed provides some support for interventions aimed at improving weight bearing through the paretic limb to establish symmetry and ultimately increase function. Although three subjects demonstrated atypical patterns, 25 subjects showed a decrease in GRF on their paretic side. Note that post-hoc analysis of the data excluding the atypical ones also resulted in significant and similar correlations between GRF symmetry and gait speed. Likewise, the significant relationship between GRF symmetry and temporal symmetry further supports intervention aimed to enhance symmetrical weight bearing. As a cautionary note, previous investigations have suggested that weight shifting activities must be practiced within the context of walking in order to enhance gait performance. In a controlled experimental study, Winstein et al. [25] found that a balance retraining program that lead to a reduction in standing balance weight-bearing asymmetry did not lead to a concomitant reduction in temporal asymmetry during gait in persons with stroke.

The higher level of association found for swing time symmetry as opposed to the symmetry in other T-D measures was also shown by several other studies [4,10,13,23]. When comparing the two temporal variables, swing time (i.e. contralateral single limb support) can be said to better represent level of impairment as it is directly related to the ability to stand on one leg as opposed to stance time which includes the double limb support periods. Similarly, as Wall and Turnbull [13] pointed out, the sensitivity of a stance time symmetry measure is lower because of the relatively larger values of stance time compared with swing time. For example, when calculating the SI, the numerator in the equation represents the difference in single limb support periods between limbs for both temporal measures, however, the denominator is always larger for the stance time variable than for the swing time variable. Thus, the use of swing time symmetry may be more appropriate when analyzing temporal gait symmetry.

The non-significant correlations found with step length symmetry was not surprising in view of the variability found in the pattern of asymmetry for this measure. In persons with chronic stroke, factors other than impairment measures, namely compensatory strategies, may increase or decrease step length of either the paretic or nonparetic limb and influence symmetry. In a study on the effect of age in gait variability, Gabell and Nayak [26] suggested that step length appears to be controlled by a gait-patterning mechanism while limb support periods may be controlled by balance.

This is the first study to report a relationship between symmetry in GRF and symmetry in T-D variables of gait in persons with stroke. A more symmetrical weight bearing between the two limbs was related to more symmetrical temporal but not distance measures during gait. This phenomenon may be explained by the same reason the level of association between gait speed and step length symmetry was lower than with the other variables. That is, GRF symmetry and temporal symmetry may be influenced by similar factors (e.g. balance) while other factors (e.g. compensatory strategies) may be more important in determining step length symmetry especially in chronic stroke survivors.

4.3. Limitations

A limitation of this study is that gait symmetry between limbs was derived with data from non-consecutive steps (i.e. different trials). However, the CV's of all T-D and GRF measures across trials were very low indicating that the measured gait variables were consistent for each subject, thus justifying the use of intrasubject average values of the paretic and nonparetic limbs. Another limitation is that sensory/perception deficits were not evaluated during the study which, together with motor deficits, could have potentially affected the degree and pattern of asymmetry. A third limitation of the study is that subjects who may normally use an assistive device for mobility outside of the home were included in the study if they were able to ambulate without the aids. However, all of these individuals have had some exposure to ambulation without aids within the confines of their home.

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