Title: Relationship between asymmetry of quiet standing balance control and walking post-stroke

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ABSTRACT

Spatial and temporal gait asymmetry is common after stroke. Such asymmetric gait is inefficient, can contribute to instability and may lead to musculoskeletal injury. However, understanding of the determinants of such gait asymmetry remains incomplete. The current study is focused on revealing if there is a link between asymmetry during the control of standing balance and asymmetry during walking. This study involved review of data from 94 individuals with stroke referred to a gait and balance clinic. Participants completed three tests: 1) walking at their usual pace; 2) quiet standing; and 3) standing with maximal loading of the paretic side. A pressure sensitive mat recorded placement and timing of each footfall during walking. Standing tests were completed on two force plates to evaluate symmetry of weight bearing and contribution of each limb to balance control. Multiple regression was conducted to determine the relationships between symmetry during standing and swing time, stance time, and step length symmetry during walking. Symmetry of antero-posterior balance control and weight bearing were related to swing time and step length symmetry during walking. Weight-bearing symmetry, weight-bearing capacity, and symmetry of antero-posterior balance control were related to stance time symmetry. These associations were independent of underlying lower limb impairment. The results support the hypothesis that impaired ability of the paretic limb to control balance may contribute to gait asymmetry post-stroke. Such work suggests that rehabilitation strategies that increase the contribution of the paretic limb to standing balance control may increase symmetry of walking post-stroke.

RESEARCH HIGHLIGHTS

- Gait and balance asymmetry are related post-stroke.
- These significant relationships are independent of limb impairment.
- Impaired paretic limb control of balance may contribute to gait asymmetry.

INTRODUCTION

Gait impairments greatly influence disability post-stroke. Of the 75% of stroke survivors who initially lose the ability to walk, only half will regain walking independence.¹ Recovery of walking function is the most frequently reported rehabilitation goal by acute stroke patients,² and gait re-training is a major focus of post-stroke physiotherapy.³

In addition to the challenges of recovering the ability to walk independently post-stroke gait is often observed to be asymmetric; one study reported 55.5% of individuals with chronic stroke exhibiting gait asymmetry.⁴ Gait asymmetry is clinically important as it has been associated with a number of proposed negative consequences with both direct and indirect lines of supporting evidence from patient populations exhibiting an asymmetric gait pattern. These proposed consequences include: 1) increased metabolic and mechanical costs;⁵ 2) increased risk for musculoskeletal degeneration and pain in the unaffected limb;⁶ and 3) decreased bone mass density in the paretic limb.⁷ Daily ambulatory activity of individuals with stroke is significantly reduced, even compared with sedentary yet healthy older adults;⁸ it is possible that any of the proposed negative consequences of persisting post-stroke gait asymmetry may contribute to this reduced level of walking activity. Besides its clinical importance, a measure of gait symmetry is distinct from gait velocity as it serves an index of the quality of gait control.⁹ Gait symmetry, unlike velocity, is not related to age;¹⁰ thus, a gait symmetry measure can be interpreted as indicating stroke-related gait impairment without concern for the confound of age.

Previous studies have attempted to understand the determinants of gait symmetry but the exact underlying causes are still unknown.^{2,4,11-14} Given the heterogeneity of the stroke population, it is likely that there are multiple determinants of gait symmetry and that individuals may exhibit asymmetric gait for different reasons. Lower limb motor impairment is correlated with gait symmetry post-stroke.^{4,12,13} More specific measures of impairment such as plantarflexor spasticity, impaired joint position sense and decreased dorsiflexor strength are correlated with temporal asymmetry while plantarflexor spasticity and impaired propulsive forces generation by the paretic leg¹⁴ are related to spatial gait symmetry.^{2,11,14} However, none of these factors explain all of the variance in post-stroke gait asymmetry. For example lower-limb motor impairment only explains approximately 40% of the variance in gait symmetry and individuals with the same level of motor impairment can exhibit asymmetric or symmetric gait.^{4,12,13}

Another potential contributing factor to gait asymmetry that has received less attention, is impaired balance control. Stance asymmetry during slow walking is related to a more posterior displacement of centre of pressure (COP) in individuals post-stroke¹⁵ indicating some relationship between standing balance and gait asymmetry. In addition, the paretic limb contributes less to quiet standing balance control than the non-paretic limb,¹⁶ indicating that the paretic limb does not have the same capacity to control standing balance as the non-paretic limb. One of many potential strategies to compensate for limited balance control during walking would be to reduce the amount of time spent in single-support on the paretic limb, which would be reflected in temporal gait asymmetry between the limbs. While Titianova and coauthors reported a relationship between a measure of standing balance and gait asymmetry, the exact contributions of the paretic limb to postural control were not known since measures were taken with a single force plate. Presently, no studies have been conducted examining the relationship between gait symmetry and standing balance control with a specific emphasis on contributions from and capacity to load the paretic limb.

The purpose of this study is to determine the relationship between symmetry of standing balance control and gait post-stroke. It was hypothesized that asymmetry of standing balance control will be associated with asymmetry during walking. Specifically, balance control asymmetry measured by increased weight-bearing on the non-paretic side, reduced weight bearing capacity on the paretic side, and decreased symmetry index of postural sway would be related to asymmetry in step length and timing during walking. Additionally, we hypothesized that these relationships would be independent of magnitude of lower-limb motor impairment. The results of this study will contribute to our

understanding of the factors that determine gait asymmetry and aid in the creation of optimal rehabilitation programs to improve gait after stroke.¹⁷

METHODS

Participants

Data for this study were obtained by retrospective chart review of individuals with stroke within a rehabilitation hospital from October 2009 to October 2011 who completed balance and gait assessments (as described below) at time of discharge. Inclusion criteria were: (1) ability to stand independently for 30s without a mobility aid; (2) ability to walk 10m without an aid and without supervision; and (3) ability to follow verbal instructions. Participants who met the following criteria were excluded: (1) previous lower limb orthopedic surgeries, prosthetics or ankle-foot orthotics; (2) history of other neurological conditions that would influence gait (e.g. Parkinson's disease); and/or (3) bilateral stroke and/or bilateral stroke-related sensorimotor impairment. Ninety four participants met these criteria and are included in the review. The following measures were extracted from clinical charts (Table 1): age, sex, type of stroke, date of stroke, affected side, Chedoke-McMaster Stroke Assessment (CMSA)¹⁸ leg and foot scores (which provide a measure lower-limb of motor impairment), Berg balance scale¹⁹ scores, and Clinical Outcomes Variable Scale²⁰ scores. The retrospective review was approved by the institution's Research Ethics Board and a waiver of patient consent for inclusion in the review was approved.

Table 1: Participant characteristics.

	Mean (or count)	Standard deviation	Minimum	Maximum
Age (years)	66	14	26	89
Sex (number)				
Women	41			
Men	53			
Stroke type (number)				
Ischemic	75			
Haemorrhagic	16			
Transforming to haemorrhagic	2			
Unknown	1			
Time since stroke (days)	54	22	22	119
Affected side (number)				
Left	35			
Right	59			
CMSA (score) ¹⁴				
Leg	5.0	1.0	2	7
Foot	4.6	1.0	2	7
Berg balance scale (score) ¹⁵	48	7	26	56
Clinical Outcomes Variable Scale (score) ¹⁶	78	9	51	91

CMSA=Chedoke-McMaster Stroke Assessment

Protocol

Standing balance measures were collected using two force plates (Advanced Medical Technology Inc, Watertown, Massachusetts, USA) positioned side-by-side with less than 1mm of separation. Patients stood in a standardized position (feet oriented at 14° from the sagittal plane with 0.17m of separation between the heels²¹) with one foot on each force plate. Patients stood quietly in two conditions: 1) quiet standing (30s duration), and 2) maximal weight-bearing (20s duration). The maximal weight-bearing trial was shorter in duration as the condition is less well-tolerated compared to the quiet standing condition. Patients were instructed to stand as still as possible with eyes open for the duration of the trials. In the maximal weight-bearing condition, patients were asked to bear as much weight as possible on the paretic side; this test reveals their overall capacity to bear weight on their paretic limb, versus spontaneous weight bearing adopted during the quiet standing condition. Ground reaction forces and moments were sampled at 256Hz, and were low-pass filtered using a 4th order dual-pass Butterworth filter at 10Hz prior to processing. Antero-posterior (AP) and medio-lateral (ML) center of pressure (COP) were calculated separately for each force plate. The root mean square (RMS) of AP and ML COP under each foot was calculated for the quiet standing trial. Weight bearing during both trials was the mean force recorded by the force plate under the non-paretic and paretic limbs, expressed as a percentage of total body.

Spatiotemporal parameters of gait were measured using the GAITRite system (CIR Systems Inc., Clifton, New Jersey, USA), which is a pressure-sensitive mat measuring 4.6m by 0.9m. This system records both the location and timing of each footfall during walking. Patients were instructed to walk along the mat at their usual pace wearing their regular footwear. Approximately 1m was provided prior to the start and at end of the mat to allow patients to accelerate and decelerate, ensuring that all footfalls recorded were representative of steady-state gait. Each participant completed enough passes to allow for at least 18 footfalls to be analyzed. Swing time, stance time and step length were calculated for each footfall using the GAITRite application software. These spatiotemporal parameters of gait were averaged for the left and right limbs separately across all completed walking trials for analysis.

Data analysis

Three primary measures of symmetry during balance were: 1) weight bearing symmetry, 2) weight bearing capacity, and 3) symmetry of RMS of COP. The symmetry index²² was used to calculate symmetry of the balance measures (i.e. weight bearing, RMS of AP COP and RMS of ML COP) and gait measures (i.e. swing time, stance time and step length).

$$\text{Symmetry Index} = \frac{\text{Value for non-paretic limb}}{(\text{Value for non-paretic limb} + \text{Value for paretic limb})}$$

The symmetry index can range from 0 to 1. A symmetry index of 0.5 indicates that the values for the paretic and non-paretic limbs are equal (i.e. perfect symmetry). If the index is greater than 0.5, the non-paretic limb has a greater value than the paretic limb for that variable.

Data were rank-transformed, and multiple regression analyses with backward selection were conducted to evaluate the relationships between the standing balance symmetry measures and each gait symmetry measure independent of lower-limb motor impairment. The gait symmetry measures were the dependent variables and the balance symmetry measures and CMSA foot and leg scores were the independent variables. The criterion for remaining in the model was alpha=0.1. The variance inflation factor was calculated to test for collinearity within the independent variables in the final models. All statistical analyses were performed using SAS 9.1 (SAS Institute Inc., Cary, NC).

RESULTS

Table 2 shows the mean balance and gait symmetry values. On average, the nature of gait and balance symmetry was similar to that observed in previous studies.^{4,23}

Table 2: Symmetry of gait and balance measures. Values presented are means with standard deviations in parentheses. Note that units refer to values for the paretic and non-paretic side; the symmetry indices are unitless values. For weight bearing symmetry and capacity, symmetry indices >0.5 indicate more weight borne on the non-paretic than the paretic limb. For RMS of both AP and ML COP, symmetry indices >0.5 indicate greater contribution of the non-paretic limb than the paretic limb to balance control. For swing time and step length, symmetry indices <0.5 indicate greater swing time duration and step length on the paretic side than the non-paretic side. Symmetry indices >0.5 for stance time indicate more time spent in stance on the non-paretic side than the paretic side.

Condition	Measure	Symmetry index	Non-paretic value	Paretic value
Quiet standing	Weight bearing symmetry (% body weight)	0.53 (0.080)	52.7 (8.0)	47.3 (8.0)
	RMS of AP COP symmetry (mm)	0.57 (0.12)	6.7 (3.1)	5.0 (2.2)
	RMS of ML COP symmetry (mm)	0.53 (0.11)	1.2 (0.6)	1.1 (0.6)
Maximal weight bearing	Weight bearing capacity (% body weight)	0.25 (0.13)	25.4 (12.9)	74.6 (12.9)
Gait	Swing time (s)	0.47 (0.06)	0.40 (0.08)	0.45 (0.09)
	Stance time (s)	0.51 (0.023)	0.95 (0.29)	0.90 (0.23)
	Step length (cm)	0.49 (0.049)	46.3 (16.3)	46.6 (15.7)

AP=antero-posterior, COP=centre of pressure, ML=medio-lateral

Results of multiple regression analyses are provided in Table 3. Weight bearing symmetry, RMS of AP COP symmetry, and CMSA foot score combined were significantly related to swing time symmetry and step length symmetry. This model explained 40% of the variance in swing time symmetry and 16% of the variance in step length symmetry. Weight bearing symmetry, RMS of AP COP symmetry, weight bearing capacity and CMSA leg score combined explained 45% of the variance in stance time symmetry. RMS of ML COP symmetry was not selected in any model of gait symmetry. Variance inflation factors in all models were less than 1.2.

In support of our hypothesis, there was a significant negative relationship between weight-bearing and RMS of AP COP symmetry and swing time symmetry independent of CMSA scores and other variables in the model ($p < 0.0018$). There was a significant positive relationship between weight-bearing and RMS of AP COP symmetry and stance time symmetry, and a significant negative relationship between weight bearing capacity and stance time symmetry, independent of other variables ($p = 0.033$). For the step length symmetry model, only weight-bearing symmetry was significantly negatively related to step length symmetry independent of the other variables in the model ($p = 0.036$).

Table 3: Results of multiple regression analysis. All balance symmetry measures and CMSA foot and leg scores were entered into the model. Backward selection was used to determine balance symmetry measures that were significantly related to gait symmetry measures (criterion for remaining in the model: $\alpha=0.1$).

Measure	Model R^2	Model p-value	Parameter estimate	Partial R^2	p-value
Swing time symmetry	0.40	<0.0001			
Intercept			0.60		<0.0001
Weight bearing symmetry			-0.24	0.13	0.0004
RMS of AP COP symmetry			-0.14	0.10	0.0017
CMSA foot score			0.018	0.12	0.00081
Stance time symmetry	0.45	<0.0001			
Intercept			0.47		<0.0001
Weight bearing symmetry			0.10	0.18	<0.0001
RMS of AP COP symmetry			0.062	0.15	0.0001
Weight bearing capacity			-0.031	0.050	0.033
CMSA leg score			-0.0049	0.077	0.0079
Step length symmetry	0.16	0.001			
Intercept			0.57		<0.0001
Weight bearing symmetry			-0.13	0.048	0.036
RMS of AP COP symmetry			-0.075	0.036	0.072
CMSA foot score			0.0084	0.031	0.092

AP=antero-posterior, COP=centre of pressure, ML=medio-lateral

DISCUSSION

The main finding of this study was that decreased involvement of the paretic limb for control of standing balance is related to the magnitude of temporal and spatial gait asymmetry. Specifically, increased weight-bearing on the non-paretic limb in quiet standing, increased contribution of the non-paretic limb to antero-posterior balance control, and reduced capacity to bear weight on the paretic limb were related to increased asymmetry of temporal and spatial features of walking. The current study reveals the association between standing symmetry and symmetry during walking. The significant relationships between symmetry of balance and symmetry of gait were independent of lower-limb motor impairment scores. This indicates that the significant relationships between symmetry of balance and gait measures are not merely due to a common link with lower-limb motor impairment.

From the results of this study, we hypothesize that asymmetric control of balance contributes to gait asymmetry independent of lower limb motor impairment. However, it is possible that the significant correlations were observed in the current study due to common factors underlying both gait and balance asymmetry, such as lesion location or sensoriperceptual impairments that contribute to both gait and balance asymmetry. For example, a previous study determined that asymmetric gait was more prevalent among those with lesions to the putamen;²⁴ a smaller putamen was also linked to balance impairment in older adults.²⁵ Therefore, the specific causal relationship between balance and gait asymmetry will need to be investigated in future work.

Weight-bearing symmetry during quiet stance was significantly related to all three gait symmetry measures. Conversely, weight-bearing capacity was only related to stance time symmetry. Typically, in quiet standing, individuals with stroke stand with increased weight on the non-paretic than the paretic limb. This could be due to reduced capacity to bear weight on the paretic limb, impaired perception of vertical,²⁶ or could reflect a preference unrelated to underlying motor or sensoriperceptual impairment. The ability to bear weight on the paretic side during the maximal weight-bearing condition may also be related to capacity for weight-bearing, perception of vertical, or a preference; these common factors underlying both weight-bearing symmetry and weight-bearing capacity may account for the lack of independent contributions from both indices of weight bearing in predicting swing time and step length symmetry. We assumed that, more so than in the quiet stance condition, maximal weight bearing would reveal reduced capacity to bear weight on the paretic limb.²⁷ Limited capacity for weight bearing on the paretic limb during standing would translate to reduced capacity to bear weight on the paretic limb during walking, which would decrease paretic stance time, thereby accounting for the significant relationship between weight bearing capacity and stance time symmetry. However, it is not clear why a similar relationship between weight bearing capacity and swing time symmetry was not observed, since swing time off the non-paretic limb reflects single support on the paretic limb.

We also evaluated the relationships between symmetry in control of COP and symmetry of walking. As expected the paretic limb had a decreased contribution to AP balance control during quiet standing.²⁸ Symmetry of RMS of AP COP was significantly related to the temporal symmetry measures. A limited range of AP COP under the paretic foot during standing could impact the ability to contribute to balance during the paretic stance phase of gait, which could result in the individual decreasing the duration of paretic stance. The non-paretic limb must then compensate for decreased paretic stance time. These results coincide with previous findings that showed decreased displacement of AP COP under the paretic limb led to impaired control of forward progression during single support on the paretic foot.²⁹ Contribution of the paretic limb to ML balance control was not related to measures of gait symmetry. The ankle invertors and evertors are largely responsible for ML COP changes under each foot;^{30,31} however, due to the small width of the foot, moments generated at the ankle in the frontal plane are limited to approximately 10Nm.³⁰ Thus, inversion/eversion moments generated at the ankle during walking are insufficient to counteract the destabilizing lateral moments during the swing phase of gait.³⁰ This limited ability of the ankle invertors and evertors to contribute to stability control could explain why changes in ML COP under each foot during quiet standing do not relate to symmetry of walking.

On average, participants in this study stood and walked asymmetrically and the pattern of asymmetry was similar to that observed in previous studies; for example, participants bore more weight on the non-paretic than the paretic limb in quiet standing,²³ and had increased swing time of the paretic compared to the non-paretic limb.⁴ However, the magnitude of asymmetry observed in the current study was lower than that observed in some previous studies;^{4,23} that is, symmetry indices were close to 0.5. It is important to note that there is a high degree of between-subject variability in asymmetry post stroke,⁴ that not all stroke patients are asymmetric in standing and walking, and that not all stroke patients display asymmetry in the 'expected' direction (e.g. some participants bear more weight on the paretic than the non-paretic limb³²). Such variability in the magnitude and direction of asymmetry could have contributed to average symmetry indices close to 0.5 in the current study. Additionally, the current study included sub-acute individuals with stroke (average time post stroke <2 months). There is evidence that at least gait asymmetry is worse in the chronic stage of stroke recovery than in the sub-acute stage.⁹ The results of this study will need to be confirmed within chronic stroke patients.

As this study involved a retrospective review, we had the advantage of seeking eligible participants from a large database of stroke patients. However, some measures that could have enhanced interpretation of the results were not available as they were not collected as part of routine care (e.g. sensation, perception, and confidence). Future studies should consider incorporating these measures to

help to clarify how stroke-related sensori-perceptual impairment impacts control of standing balance and walking.

The results of this study are potentially clinically relevant. Asymmetry of balance control could help to explain gait asymmetry post-stroke. Furthermore, this relationship suggests potential targets for rehabilitation intervention to improve gait symmetry. Specifically, exercises that train weight-bearing symmetry and control of COP within the foot base of support in the AP direction may be of benefit. Previous work has found that individuals with stroke have the capacity to improve weight bearing symmetry with a variety of training approaches including compelled body weight shifting³³ and visual biofeedback.^{34,35} In some cases an improvement in weight bearing symmetry in standing was associated with an improvement in gait measured by either velocity³³ or paretic limb weight-bearing during walking.³⁵ Future work should examine the effects of training control of AP COP with the paretic limb as well the effects of both this intervention and weight bearing symmetry training on gait symmetry specifically.

CONCLUSIONS

Overall, weight bearing asymmetry and decreased contribution of the paretic limb to control of quiet standing was related to increased gait asymmetry. These significant relationships were independent of lower-limb motor impairment. Further research is needed in this area to determine a causal link between asymmetric control of balance and gait, and to identify other factors that can help to explain gait asymmetry.

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