Title: Determinants and consequences for standing balance of spontaneous weight-bearing on the paretic side among individuals with chronic stroke

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ABSTRACT

Hemiparetic stroke patients commonly bear more weight on the non-paretic side which seems intuitively linked to unilateral control deficits. However, there is evidence that some post-stroke favour weighting the paretic side, which may be problematic given altered capacity of the paretic limb to contribute to the control of upright posture. This study explores the prevalence and clinical determinants of stance asymmetry, and the relationship between stance asymmetry and postural control among chronic stroke patients. Subjects (n=147; >6 months post-stroke) stood on two force plates in eyes-open and eyes-closed conditions; 59 were symmetric, 18 had paretic asymmetry (PA), and 70 had non-paretic asymmetry (NPA). Root mean square (RMS) of antero-posterior and medio-lateral centre-of-pressure under each limb and both limbs combined were compared. RMS of total medio-lateral centre-of-pressure was greater for both asymmetric groups compared with the symmetric group. PA subjects relied less on the loaded limb for control than NPA subjects and relied more on visual information for postural control than those who were symmetric. There were no differences in the characteristics of individuals between the PA and NPA groups. The loading of the paretic limb was not related to impaired postural control during stationary standing which was attributable, in part, to individuals relying on control from the non-paretic limb, in spite of lower vertical load, and a greater dependence on visual contributions. There was no evidence that greater loading on the paretic limb was related to persisting dyscontrol but may rather reflect a learned strategy.

RESEARCH HIGHLIGHTS

- Some individuals post-stroke stand with more weight on the paretic limb.
- There is no evidence for a clinical profile of paretic asymmetry.
- Paretic asymmetry appears to promote reliance on vision for balance control.

INTRODUCTION

The distribution of weight between legs is an important aspect of balance control post-stroke. Favouring the non-paretic limb can reduce reliance on the more impaired limb for balance control. Typically, stroke patients have difficulty maintaining a weight shift to their paretic side,¹ and there is greater postural sway when loading the paretic compared to the non-paretic leg during quiet standing.² The contribution of the paretic leg to balance control, in terms of the amount of corrective antero-posterior (AP) torque generated at the ankle, is less than that of the non-paretic leg even if weight distribution is symmetric.³⁻⁵ Thus, the centre-of-mass should be shifted toward the non-paretic side when standing to minimize instability due to unilateral limb impairment;⁵ indeed, many chronic hemiparetic stroke patients stand with more weight on their non-paretic side.⁶⁻⁹

Despite the apparent benefits when standing still in favour of the non-paretic limb there is evidence that some post-stroke favour standing over the paretic limb;¹⁰ this stance strategy potentially leads to instability. Among healthy individuals who stand asymmetrically, the more-loaded limb contributes more to balance control than the less-loaded limb.^{4,11} However, weight-bearing on the paretic limb, which likely has reduced capacity to contribute to balance control,³⁻⁵ would result in instability.² Such instability may be exacerbated with removal of vision. Individuals with stroke show greater reliance on vision for standing balance control than healthy individuals,^{9,12} possibly due to reduced sensory inputs from the paretic limb.¹³ During asymmetric stance among healthy individuals it is speculated that unloading one limb decreases the activity of plantar cutaneous mechanoreceptors from that limb and, therefore, reduces the relevance of sensory input from that limb to balance control.¹⁴ Loading the paretic limb, thereby influencing the reliance on sensory input from the intact non-paretic limb, potentially further increases reliance on vision for balance control. Therefore, we believe that there are important implications to understanding the prevalence, determinants and consequences of stance asymmetry post-stroke.

There are several possible explanations for standing asymmetry that favours increased loading on the paretic limb. Contraversive pushing is a perceptual disorder commonly observed in acute stroke whereby patients lean toward the affected side and actively resist any attempt to correct this posture.^{15,16} While clinical measurement of pushing behaviour commonly resolves in the earlier stages of stroke recovery,¹⁵ weight bearing on the paretic side among chronic stroke patients might indicate residual pushing behaviour. Pushing has been linked to hemispatial neglect and is more common among those with right-hemisphere lesions than left-hemisphere lesions.¹⁶ Additionally, it is possible that asymmetric stance over the paretic limb occurs among those stroke patients with less sensori-motor impairment than those who weight-bear on the non-paretic limb. Alternatively, asymmetric loading in favour of the paretic limb may reflect a strategy influenced by rehabilitation or related to the capacity to generate other balance reactions such as rapid stepping with the non-paretic limb.¹⁷

This study aims to: 1) determine the prevalence, among chronic stroke patients, of stance strategies emphasising weight bearing over the paretic limb; 2) determine the individual characteristics that predict reliance on paretic limb during stance; and 3) determine the consequences of asymmetry for standing balance control. With respect to prevalence we predicted, on the basis of previous work,^{9,10} that approximately 10-30% of individuals after stroke will stand quietly favouring the paretic limb. With respect to individual determinants of stance asymmetry we predicted persisting evidence of neglect, but not degree of sensory or motor impairment, would be associated with stance towards the paretic side.^{15,18} We hypothesised that stroke patients who bore more weight on their paretic limb would sway more than those who bore more weight on their non-paretic limb. Additionally, despite weight-bearing asymmetry, which should increase the contribution of the more-loaded limb to balance control,⁴ we hypothesized that the paretic limb would contribute less to balance control than the non-paretic limb. Finally, we expected that hemiparetic subjects weight-bearing on the paretic side may be more dependent on vision to offset any diminished sensory feedback from the impaired limb.

Therefore, we predicted that removal of vision would result in a greater increase in sway for subjects bearing more weight on the paretic side than those bearing more weight on the non-paretic side.

METHODS

Data for this study were gathered as part of the [database name removed]. Individuals with stroke receiving treatment at one of four participating hospitals (one acute care and three rehabilitation hospitals) were recruited for this database. The purpose of the database is to characterize sensori-motor and cognitive recovery post-stroke. Participants were included in the current analysis if they completed assessment of quiet standing balance (as described below) 6-months post-stroke or later. Participants were excluded if their stroke(s) affected both hemispheres and/or if they had bilateral sensorimotor impairment of both limbs; 147 individuals met the inclusion and exclusion criteria and were included in the analysis. This study was approved by the Research Ethics Board at each participating institution and subjects provided written informed consent to participate.

Participant characteristics are presented in Table 1. Demographic information and information regarding time of stroke, stroke location and affected side was obtained from review of subjects' hospital charts. Stroke severity was determined using the National Institutes of Health Stroke Scale¹⁹ (NIH-SS). The existence of sensory impairment was determined using the sensory item on the NIH-SS. The existence of perceptual problems was determined using the extinction item on the NIH-SS, and the line bisection test.²⁰ For the line bisection test, subjects were asked to place a mark in the centre of a 20cm-long line on a piece of paper. This test was repeated three times and an average deviation from the centre was calculated. Subjects who deviated by 2.8% or more of the length of the line to the right of centre or 3.6% or more of the length of the line to the left of centre were determined to have neglect.²¹ To determine if asymmetry was related to prior history of 'pushing', the Scale for Contraversive Pushing (SCP)²² score was obtained from assessments completed upon admission to in-patient rehabilitation (i.e. sub-acute phase). Lower-limb motor impairment was determined using the leg and foot scores of the Chedoke-McMaster Stroke Assessment²³ (CMSA-leg and CMSA-foot).

Postural sway was measured by root mean square (RMS) of the COP displacement^{9,24} of subjects standing on two force plates with eyes open and eyes closed (one trial in each condition). The force plates were positioned side-by-side so that they were as close together as possible without touching (i.e. <1mm apart). Subjects stood in a standardised position (feet oriented at 14° with 0.17m between the heels²⁵) with each foot equidistant from the gap between the force plates. Participants were instructed to stand as still as possible for 30s, looking straight ahead at a mark on the wall at eye level. Balance testing was conducted in a quiet room with no distractions. Ground reaction forces and moments were sampled at 200Hz and were low-pass filtered using a 4th order dual-pass Butterworth filter at 10Hz prior to processing. AP and ML COP were calculated separately for both force plates and total COP under both feet combined was also calculated.

Weight-bearing asymmetry was the mean vertical force recorded by the force plate under the non-paretic limb over the duration of the trial and was expressed as a percentage of total body weight. We determined the normal range of weight-bearing for healthy individuals from published values;^{10,26} a conservative estimate of this range is 47-53%. Therefore, participants were deemed to be asymmetric toward their paretic side (paretic asymmetry; PA) if they bore <47% body weight on the non-paretic side, and to be asymmetric toward their non-paretic side (non-paretic asymmetry; NPA) if they bore >53% body weight on the non-paretic side. Participants who loaded 47-53% body weight on the non-paretic side were classified as symmetric. Asymmetry magnitude was calculated as the absolute difference between 50% and the percentage of total body weight on the more-loaded limb.

Table 1: Characteristics of entire subject cohort. Values presented are means with standard deviations in parentheses or proportions. The p-value is for the comparison between the three sub-groups from a one-way ANOVA (ordinal or continuous data) or chi-square (count data).

	Entire sample	Asymmetric		Symmetric	p-value
		Paretic	Non-paretic		
Number of participants	147	18	52	59	
Proportion of women	60/147	8/18	21/52	26/59	0.91
Age (years)	67.4 (12.6)	71.8 (9.9)	67.9 (13.1)	67.5 (13.4)	0.45
Time since stroke (months)	12.9 (15.6)	16.8 (19.9)	10.8 (5.3)	15.2 (21.2)	0.26
Right-hemisphere affected	74/147	11/18	24/52	23/59	0.28
NIH-SS [*]	2.6 (2.6)	2.3 (2.5)	3.3 (2.9)	1.5 (1.8)	0.0007
Sensory impairment	42/147	4/18	15/52	11/59	0.44
Extinction	16/147	1/18	8/52	2/59	0.070
History of pushing (N=101)	13/101	1/8	6/36	2/44	0.20
Neglect (N=109)	22/109	3/11	6/39	9/43	0.64
CMSA-foot [†] (N=119)	4.7 (1.5)	4.6 (1.7)	4.6 (1.4)	5.5 (1.2)	0.0066
CMSA-leg [‡] (N=117)	5.2 (1.2)	5.0 (1.0)	5.0 (1.2)	5.8 (1.0)	0.0018

^{*}National Institute of Health Stroke Scale; score ranges from 0 to 42, with higher values indicating a more severe stroke

[†]Chedoke-McMaster Stroke Assessment foot score; score ranges from 1 to 7, with lower values indicating greater impairment

[‡]Chedoke-McMaster Stroke Assessment leg score; score ranges from 1 to 7, with lower values indicating greater impairment

RMS of total, left-foot and right-foot COP displacement were calculated separately in the ML and AP directions. The contribution of the more-loaded limb to balance control was calculated by dividing the RMS of COP in each direction under the more-loaded limb by the sum of the RMS of COP under both limbs.¹¹ A value of 0.5 indicates that both limbs contribute equally to standing balance control. Typically, the more-loaded limb contributes more to the control of quiet standing than the less-loaded limb;^{4,11} therefore, this ratio is expected to be greater than 0.5 for asymmetric individuals. The Romberg quotient was calculated to determine the degree of reliance on visual information for postural control; the Romberg quotient was defined as the RMS of total AP and ML COP for eyes-closed divided by RMS of total AP and ML COP for eyes-open.

To determine potential clinical associations with weight-bearing asymmetry, demographic and clinical measures were compared between the three groups (PA, NPA and symmetric); one-way analysis of variance (ANOVA) was used for ordinal (e.g. CMSA scores) and continuous measures and chi-square test was used for count data. To assess differences in balance control between the three groups a one-way ANOVA was used to compare RMS of total AP and ML COP, contribution of the more-loaded limb to balance control, and Romberg quotients between the three groups. Tukey's HSD was used to determine which groups differed. If significant differences were found on the chi-square test for a given variable, the test was repeated comparing each pair of groups separately to determine which groups differed on that variable. Data were rank-transformed prior to analysis to allow for non-parametric analysis due to the non-normal distribution of several outcome variables.

RESULTS

Prevalence

The first objective was to establish prevalence of stance asymmetry favouring the paretic side. Overall, 12.2% of individuals (18/147) showed PA in the eyes-open trial. Of the remaining 129 individuals 70 (47.6%) were classified as asymmetric but favouring the non-paretic limb (NPA) and 59 (40.1%) were symmetric (see Figure 1). On average, NPA subjects bore 61.5% body weight on the non-paretic limb (standard deviation: 7.3%), PA subjects bore 56.1% body weight on the paretic limb (standard deviation: 3.1%) and symmetric subjects bore 50.0% body weight on the non-paretic limb (standard deviation: 1.8%). Absolute asymmetry magnitude was significantly different between all three groups ($p < 0.0001$).

Figure 1: Histogram showing the distribution of loads borne on the non-paretic limb across the study sample.

Because the NPA group was so much more asymmetric than the PA group, we limited further analysis to those individuals in the NPA group with similar absolute asymmetry magnitude as the PA group. The highest absolute asymmetry in the PA group was 13.5%; therefore, all participants in the NPA group with $>13.5\%$ absolute asymmetry ($n=18$) were excluded from further analysis leaving a total of 52 subjects for comparison to the PA group.

Individual determinants of stance symmetry

Subjects in the three groups (i.e. PA, NPA, and symmetric) did not differ in terms of their sex, age, time post-stroke, affected hemisphere, affected side of body, or prevalence of sensory impairment (Table 1). Stroke severity (NIH-SS) and lower-limb motor impairment (CMSA-foot and -leg scores) differed between the three groups. Post-hoc analysis revealed that these differences were due to differences between the NPA and symmetric groups ($p < 0.05$); the NPA group had more severe strokes and motor impairment than the symmetric group. There were no significant differences between the PA and NPA groups on these measures. With respect to the specific relationship to perceptual disorders, there were no significant differences between the three groups for prevalence of neglect, history of pushing, or prevalence of extinction.

Impact of stance symmetry on balance control

RMS of total ML COP differed between the three groups ($p=0.0062$; Figure 2). Post-hoc analysis revealed that the NPA and PA groups had significantly higher RMS of total ML COP than the symmetric group ($p < 0.05$). There were no significant differences between the three groups for RMS of

AP COP. The contribution of the more-loaded limb to balance control in AP direction differed between the three groups ($p=0.0058$; Figure 3). Post hoc analysis revealed that the NPA group had a higher contribution value than the PA group ($p<0.05$). There was no significant difference in contribution of the more-loaded limb to balance control in the ML direction between the three groups ($p=0.33$). The AP Romberg quotient differed between the three groups ($p=0.0042$; Figure 4). The PA group had a significantly higher AP Romberg quotient than the symmetric group ($p<0.05$). There was no difference in the ML Romberg quotient between the three groups ($p=0.45$).

Figure 2: Root mean square (RMS) of medio-lateral (ML) and antero- centre (AP) of pressure (COP) position for eyes-open trials. Values presented are means with standard deviation error bars. There was a significant difference between the three groups for RMS of ML COP ($p=0.0062$) but not RMS of AP COP ($p=0.72$). Tukey's HSD revealed that the NPA and PA group had significantly higher RMS of ML COP than the symmetric group ($*p<0.05$).

Figure 3: Contribution of the more-loaded limb to balance control in the ML and AP directions. The contribution is the RMS of COP for the more-loaded limb divided by the sum of RMS of COP for both limbs; values greater than 0.5 indicated that the more-loaded limb contributed more to the control of balance than the less-loaded limb. Values presented are means with standard deviation error bars. There was a significant difference between the three groups for AP contribution ($p=0.0058$) but not ML contribution ($p=0.33$). Tukey's HSD revealed that the NPA had a significantly higher contribution value than the PA group ($*p<0.05$).

Figure 4: Romberg quotients for the three groups in the medio-lateral (ML) and antero-posterior (AP) directions. The Romberg quotient is the RMS of COP in the eyes closed condition divided by the RMS of COP in the eyes open condition; values greater than 1 indicate increased postural sway with eyes closed compared to eyes open. Values presented are means with standard deviation error bars. The Romberg quotient in the AP direction was significantly different between the three groups ($p=0.0042$); there was no significant difference between the groups for the ML Romberg quotient ($p=0.45$). Tukey's HSD revealed that the PA group had a significantly higher AP Romberg quotient than the symmetric group (* $p<0.05$).

DISCUSSION

To our knowledge, this is the first study reporting the prevalence and consequences of spontaneous asymmetric stance toward the paretic side in chronic stroke patients. With respect to prevalence, approximately 12% of stroke patients bore significantly more weight on the paretic than the non-paretic limb. We found no evidence for a significant difference in clinical profile between these individuals. Importantly, there was no specific association between stance asymmetry and previous evidence of spatial neglect or contraversive pushing. The third objective was to determine the consequences of asymmetry for standing balance control. In support of our hypothesis, there was a significant increase in ML postural sway among those who bore more weight on the paretic limb compared to those who stood symmetrically; however, there was no difference in postural sway between the two asymmetric groups.

One might imagine that stance asymmetry could be associated with persisting dyscontrol or an adaptive strategy. Dyscontrol may arise from the persistence of perceptual deficits, such as stroke patients with 'pushing' syndrome who shift weight toward the paretic side and actively resist attempts to correct posture to upright.²⁷ Asymmetric stance may be associated with a continuing misperception of vertical, as has been suggested for pushing,²² and as shown with acute stroke patients, where subjective visual vertical was offset in the same direction as the lean side during quiet stance, regardless of the side of hemiparesis.²⁸ Pushing usually resolves within the early stages of stroke recovery, although signs of pushing can persist 3-6 months post-stroke.^{15,29} We wished to determine if paretic asymmetry was a sub-clinical residual sign of previous pushing behaviour. However, there was no evidence that those in the PA group were more likely to have past history of pushing than those in the NPA group.

Based on these results one is led to the possibility that standing with more weight on the paretic limb is associated with a strategic preference rather than the product of persisting dyscontrol. This may reflect a strategy learned during rehabilitation to try to favour the paretic limb or a pre-planned strategy to permit a rapid compensatory step with the non-paretic leg in the event of instability.¹⁷

Contrary to our hypothesis, bearing more weight on the paretic limb did not influence overall postural control with eyes open. However, there were differences in the contribution of each limb to balance control between the two groups. Typically, the more-loaded limb will contribute more to balance control than the less loaded limb,^{4,11} which is evident in greater RMS of COP under the more loaded than the less-loaded limb. This was observed for participants in the NPA group in the AP direction but not for participants in the PA group. On average the AP contribution of the more-loaded limb within the PA group was less than 0.5, indicating that the more-loaded (paretic) limb does not contribute more to balance control than the less-loaded limb. Because the paretic limb did not contribute more to balance control than the non-paretic limb, this suggests that the asymmetric posture is not chosen due to increased capacity of the paretic limb to contribute to balance control. Between-group differences in limb contribution to standing balance control were only observed in the AP direction, not in the ML direction. A previous study among young adults found that limb contribution in the ML direction was not affected by asymmetric stance.¹¹ Given that ML ankle movements have little influence on overall COP, examination of single-limb ML COP fluctuations may not be as meaningful as single-limb AP COP fluctuations.³⁰

Postural sway typically increases with eyes closed compared to eyes open and the magnitude of increase in sway from eyes open to eyes closed indicates the degree of reliance on visual information for balance control. Individuals with stroke show greater reliance on visual information for standing balance control than healthy individuals.^{9,12} In the current study, the magnitude of increase in AP sway from eyes open to eyes closed was greater for PA subjects than symmetric subjects, indicating that PA subjects had greater reliance on visual information than symmetric subjects. It is possible that this finding was due to diminished sensory inputs from the more loaded paretic limb compared with the non-paretic limb. The current study contrasts with a previous study, which found that individuals with low stance asymmetry post-stroke had higher Romberg quotients than those with high asymmetry.⁹ However, individuals with paretic asymmetry were included in the 'low asymmetry' group. Therefore, it is possible that increased visual reliance among those who bear more weight on the paretic limb lead to these unexpected findings.

This study is potentially limited by our classification into three discrete groups and the cut-off values for denoting asymmetry. Based on previous published values for healthy individuals we defined the normal range of weight bearing as 47-53% body weight on one limb. Individuals who showed weight-bearing outside of this range were classified as asymmetric. It is possible that this range over-estimates overall prevalence of asymmetry given that healthy individuals can show weight-bearing asymmetry outside of this range.¹⁰ Furthermore, standing balance was assessed with one trial in each condition during a single test session. While the side of asymmetry persisted across both trials the trial-to-trial repeatability of asymmetry amplitude needs to be determined. Additionally, further work is required to determine if asymmetry toward the paretic side resolves with time post-stroke. In the current study, the relatively large sample revealed only 18 subjects (12%) who bore more weight on the paretic than the non-paretic limb. The small size of the PA group may have limited our power to detect clinical differences between this and the NPA and symmetric groups. While the database captured information regarding motor impairment and perceptual disorders, a thorough battery of sensory tests was not included. Therefore, this study is limited by the inclusion of a gross measure of sensory impairment (from the NIH-SS) rather than inclusion of sensory measures relevant to balance control, such as plantar cutaneous sensation, ankle proprioception and vision. More specific sensory measures may be more likely to reveal relationships to stance asymmetry.

To conclude, we have identified that a number of hemiparetic stroke patients spontaneously stand with weight distributed over their paretic limb. It is not currently known why this stance is adopted; however, it appears that there is no benefit to standing balance control of a weight-bearing strategy favouring the paretic limb. Weight-bearing on the paretic limb appears to promote reliance on visual feedback for antero-posterior control of standing balance.

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