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Between-limb synchronization for control of standing balance in individuals with stroke

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ABSTRACT

Background: During standing, forces and moments exerted at the feet serve to maintain stability in the face of constant centre-of-mass movement. These actions are temporally synchronized in healthy individuals. Stroke is typically a unilateral injury resulting in increased sensori-motor impairment in the contra-lesional compared with the ipsi-lesional lower-limb, which could lead to reduced between-limb synchronization for control of standing balance. The purpose of this study is to investigate between-limb synchronization of standing balance control in individuals with stroke; a potentially important index of control of upright stability.
Methods: Twenty healthy controls and 33 individuals with unilateral stroke were assessed. Stability was assessed during a 30-second quiet standing trial by measuring data from two force plates (one per foot). Limb-specific centre of pressure was calculated. Between-limb synchronization was defined as the coefficient of the correlation between the left and right foot for both the antero-posterior and medio-lateral centre of pressure time series. Synchronization, weight-bearing symmetry, and root mean square of the total centre of pressure excursion were compared between controls and stroke participants.
Findings: Stroke participants swayed more, were more asymmetric, and had less between-limb synchronization than healthy controls. Among individuals with stroke, reduced between-limb synchronization was related to increased postural sway in the medio-lateral direction and increased weight-bearing asymmetry.
Interpretation: Individuals with stroke have reduced temporal synchronization of centre of pressure fluctuations under the feet when controlling quiet standing. The clinical significance of reduced synchronization remains to be determined, although it appears linked to increased medio-lateral sway and weight-bearing asymmetry.
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1. Introduction

Individuals with stroke have a high incidence of falls (Forster and Young, 1995), which may be linked to impaired standing balance control compared to aged-matched controls (Geurts et al., 2005). Further understanding of the underlying challenges to balance control after stroke is required. One approach to quantitatively assess balance control is the measurement of postural sway in standing using force plates. In many populations, a composite measure of centre of pressure (COP) sway reveals balance control challenges and increased falls risk (Maki et al., 1992). Current postural sway measures typically examine excursion of the total COP under both feet combined. However, the application of this approach is complex after stroke due to the possible contribution of limb-specific control problems and/or central balance control challenges. For individuals post-stroke, the interest is not only in the overall COP excursion, but the interpretation of this compromised control, specifically related to paretic-limb control and strategy to stand (e.g. weight-bearing asymmetry). It is likely that a single composite measure of COP will be inadequate to reveal underlying determinants of balance control. As a result, we view it important to specifically understand the paretic limb control (limb specific coupling to the non-paretic limb) and the strategy (stance symmetry) to complement more conventional measures of overall COP.

A previous study used two force plates to analyse COP profiles under each foot separately in individuals with stroke (Genthon et al., 2008b). This study, which was limited to examination of typical amplitude and frequency COP measures under each foot, found that

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the non-paretic lower-limb contributes more to the control of standing balance than the paretic limb. Measurement of COP profiles under each foot during standing can also be used to examine correlation of COP profiles in time. The strength of the correlation can indicate between-limb synchronization of stability control (Winter et al., 1993). Between-limb correlations of antero-posterior (AP) and medio-lateral (ML) COP profiles reveal moderate to high correlation coefficients in healthy individuals (Mochizuki et al., 2005; Winter et al., 1993).

We argue that use of two force plates to assess standing balance in individuals with stroke can provide information on three potentially independent measures of control of standing posture: 1) weight-bearing symmetry, 2) contribution of each limb to maintenance of stable posture, and 3) synchronization between the limbs. The purpose of this study is to examine differences in between-limb synchronization in individuals with stroke compared to healthy controls, and to determine if asynchrony is related to the control of postural sway and stance loading asymmetry.

2. Methods

Data for this study were gathered as part of the Heart and Stroke Foundation Centre for Stroke Recovery Longitudinal Database. Individuals with stroke receiving treatment at one of the four participating hospitals (one acute care and three rehabilitation hospitals) were recruited for this database. The purpose of the database is to monitor sensori-motor and cognitive recovery post-stroke. Data from the initial assessment of 33 consecutive participants who met the inclusion/exclusion criteria and had completed a standing balance test (as described below) were included in this study. The inclusion criteria for individuals selected for this specific study were: 1) able to stand independently (no aid or physical support) for at least 10 s, and 2) able to understand and follow instructions. Individuals with bilateral strokes or measurable sensori-motor impairment in both lower limbs, as assessed with the Chedoke-McMaster Stroke Assessment (Gowland et al., 1993), were excluded. For comparison, 20 healthy controls with no known neurological or musculoskeletal illness or injury that could affect balance control were also recruited and completed the same balance test. Participant characteristics are described in Table 1. This study was approved by the Research Ethics Board at each participating institution and subjects provided written informed consent prior to participation.

Two force plates were positioned side-by-side so that they were as close together as possible without touching (<1 mm apart). Subjects stood with one foot on each force plate in a standardized position (feet oriented at 14° with 0.17 m between the heels (McIlroy and Maki, 1997)) with each foot equidistant from the midline between both plates. Subjects were instructed to stand as still as possible for 30 s. Ground-reaction forces and moments were sampled at 200 Hz, and were low-pass filtered using a 4th order dual-pass Butterworth filter at 10 Hz prior to processing. AP and ML COP were calculated separately for both force plates and the total COP under both feet combined was also calculated.

The AP and ML COP and force time series' for each force plate were divided into five-second-long epochs and outcome variables were calculated for each epoch. Note that it was necessary to crop 5 s of data for one trial of one healthy control (due to a technical error) and 10 s of data from one trial from one stroke participant (due to reduced standing tolerance). As a result, there were 119 healthy control epochs (20 subjects × 6 epochs − 1 epoch) and 196 stroke participant epochs (33 subjects × 6 epochs − 2 epochs) available for analysis.

Stance load symmetry was defined as the mean force recorded by the force plate under the affected (or non-dominant) limb and was expressed as a percentage of body weight. Absolute stance load symmetry was defined as the mean force recorded by the force plate under the less-loaded limb. The root mean square (RMS) of the AP and ML COP time series was calculated for each force plate and for total COP under both feet; the RMS provides a measure of the amplitude of postural sway (de Haart et al., 2004). Synchronization of COP motion between both feet was calculated by cross-correlating COP under the left and right foot. The mean AP and ML COP was subtracted from the time series and the right and left COP were cross-correlated on a point-by-point basis (Mochizuki et al., 2005). The correlation coefficient at time zero was determined (ρ_0) as COP motion should be synchronized at the same point in time (Winter et al., 1993). To account for potential time lag in COP fluctuations in both limbs, the peak of the cross-correlation function within ±1 s of time zero (ρ_{max}), and the timing of the peak lag were also determined (Fig. 1).

Table 1
Participant characteristics. Values presented are means (standard deviation; range), or counts.

	Stroke participants	Healthy controls
Age (years)	61 (14; 28–90)	27 (5; 20–37)
Sex (number)		
Women	10	9
Men	23	11
Time since stroke (days)	133 (194; 10–861)	–
Time since stroke (number)		
<1 month	9	–
1–3 months	9	–
3–6 months	9	–
6 months–1 year	3	–
>1 year	3	–
Affected or non-dominant side (number)		
Left	17	19
Right	16	1
National Institutes of Health Stroke Scale (Goldstein et al., 1989)	4.6 (4.1; 0–15)	–
Chedoke-McMaster Stroke Assessment (Gowland et al., 1993)		
Leg	4.6 (1.3; 3–7)	–
Foot	4.2 (1.6; 1–7)	–
Berg Balance Scale (Berg et al., 1989)	37.9 (15.6; 4–56)	–

In order to estimate the strength of the correlations that might be obtained due to random chance, the cross-correlation function was calculated in cases where two signals are uncorrelated. Twenty 30-second long simulated signals were generated. These signals consisted of a sine wave (amplitude: 2 units, range: −1 to +1, period: 3.14 s) paired with a series of randomly-generated numbers that ranged between −1 and +1. The sine wave served as the COP under one foot, and the random numbers served as the COP under the other foot. The signals were analysed, as described above, to determine ρ_0, ρ_{max} and the ρ_{max} lag (Fig. 1).

Repeated measures analysis of variance (ANOVA) on rank-transformed data was used to compare RMS of total AP and ML COP, and RMS of AP and ML COP under each foot, stance loading asymmetry, and between-limb AP and ML COP correlations between the two subject groups (healthy controls and stroke participants). A *t*-test was used to determine if the time lag in ρ_{max} was different from zero. Synchronization, weight-bearing asymmetry and postural sway variables were averaged for each subject and Spearman correlations were used to explore relationships between these variables in stroke participants. For all statistical analyses alpha was set at 0.05.

3. Results

Stroke participants showed increased postural sway compared with controls (Table 2); RMS of total AP and ML COP, and RMS of AP and ML COP under both limbs were higher in individuals with stroke than controls (Ps < 0.0006). In general, AP COP under each foot was positively correlated, and ML COP was negatively correlated (Fig. 1).

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