Reliability of two methods for identifying the postural phase of gait initiation in healthy and post-stroke subjects

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Conflict of interest disclosure: The authors declare that there are no conflicts of interest.

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Abstract

This study aims to compare two methods of assessing the postural phase of gait initiation as to intrasession reliability, in healthy and post-stroke subjects. As a secondary aim, this study aims to analyse anticipatory postural adjustments during gait initiation based on the centre of pressure (CoP) displacements in post-stroke participants. The CoP signal was acquired during gait initiation in fifteen post-stroke subjects and twenty-three healthy controls. Postural phase was identified through a baseline-based method and a maximal displacement based method. In both healthy and post-stroke participants higher intra-class correlation coefficient and lower coefficient of variation values were obtained with the baseline-based method when compared to the maximal displacement based method. Post-stroke participants presented decreased CoP displacement backward and toward the first swing limb compared to controls when the baseline-based method was used. With the maximal displacement based method, there were differences between groups only regarding backward CoP displacement. Postural phase duration in medial-lateral direction was also increased in post-stroke participants when using the maximal displacement based method. The findings obtained indicate that the baseline-based method is more reliable detecting the onset of gait initiation in both groups, while the maximal displacement based method presents greater sensitivity for post-stroke participants.

Keywords: gait initiation; postural control phase; stroke; reliability; centre of pressure

Word count: 3969

Abstract word count: 199

Number of tables: 2

Number of figures: 2

Introduction

Gait initiation is an important part of locomotion and has been described as the transient state between two steady states - standing and walking.[1,2] This transition from a quasi-static state (quiet standing) to a dynamic state (walking) is considered to be governed by a motor program, as stereotyped patterns of activity, soleus inhibition and tibialis anterior activation, and invariant relative timing have been demonstrated.[3,4] These first phase mechanisms, namely anticipatory postural adjustments, are responsible for moving the centre of pressure (CoP) under the feet backward and toward the first swing limb.[5-7] In turn, CoP displacement increases anterior-posterior and medial-lateral components of the ground reaction force, thereby generating momentum in those directions for taking a step before the centre of mass moves out of the base of support.[4,7] Thus, the central nervous system uses stable, efficient mechanisms for dealing with the inherent instability of upright bipedalism during gait initiation.[8,9] For this reason, CoP displacement backward and toward the first swing limb has been identified as the postural phase of gait initiation.[10-14]

Disturbance of gait initiation is common in patients with central nervous system impairment, like stroke. In this condition, postural adjustments' dysfunction during the postural phase is related to disturbance in the first step.[15-18] However, despite the importance of the postural phase in gait initiation performance, there has been a poor standardisation of methods to identify the onset of the postural phase of gait initiation, as different variables have been used: centre of mass migration and acceleration, ground reaction force and CoP related variables.[10-15,18-22] Whereas studies assessing the centre of mass and ground reaction force stated how the event was computed, the same is not observed in studies involving CoP related variables.[10-15,18,20-22] Since gait initiation is the transition between standing and walking, two methods used in centre of mass displacement evaluation may be transferred to CoP variables: 1) one based CoP displacement during upright standing (baseline-based method), and 2) another based on maximal CoP displacement backward and toward the first swing limb (maximal displacement based method).[20-22] While the methods used to identify the beginning of the postural phase of gait initiation are poorly standardised, the end of the postural phase has been identified most often as the instant where the CoP reaches its maximum backward and toward the first swing limb positions.[10,12,13] The methods used in studies assessing the centre of mass can be transferred to CoP variables to identify the onset of the postural phase of gait initiation. However, it is important to know their reliability, as this analysis has not been done yet.

Given the postural phase impacts on forward displacement performance, it is important to select a reliable method to assess this particular phase of gait initiation as measurement errors can seriously affect statistical analysis and interpretation.[23] This should be analysed in healthy subjects, but also in subjects with lower performance in gait initiation as post-stroke subjects.[24,25] Such knowledge has the potential to provide a foundation for answering research questions about the most reliable method to assess the postural control phase of gait initiation in pathologic and non-pathological conditions, and to assess motor control, as the onset of CoP displacement is a key event for electromyography analysis when postural adjustments are investigated.[26,27] From a clinical point of view, this study contributes to establish how outcomes of interventions can be quantified to assess postural control measures.

The aim of the present study was to compare the reliability of CoP displacements during the postural phase of gait initiation calculated by two methods of detection the beginning of the postural phase (baseline-based vs. maximal displacement based methods) in health and post-stroke participants. For this, the intra-session reliability was calculated to assess the variability of each method.[28] As secondary aim, this study analysed anticipatory postural adjustments based on the CoP displacements in post-stroke participants. Based on the findings obtained by Breniere (1996) that the natural body frequency (ratio between the amplitude of the centre of mass and of the CoP) is an absolute invariant parameter, specific to human standing and gait, it can be hypothesised that CoP displacement values calculated with the baseline-based method than with the maximal displacement based method are more reliable.[29] As to the secondary purpose, based on the results obtained by Brunt (1995), demonstrating weight bearing asymmetry in subjects with stroke, and by Hesse et al. (1997), demonstrating changes in temporal muscle sequence during gait initiation, it can be hypothesised that post-stroke subjects present decreased CoP shift backward and toward the swing limb regardless of the method used.[16,30]

Methods

Participants

Fifteen patients who had suffered a stroke at least 6 months earlier (8 females, 7 males) and 23 healthy participants (12 females, 11 males) participated in this study (demographic descriptors can be found in Table 1). The mean time between their stroke and the time of inclusion in this study was 24.9±11.5 months (6-40 months). All post-stroke participants suffered an ischemic stroke at the subcortical level (internal capsule): 8 of them had suffered an infarction in their left hemisphere, whereas 5 had suffered an infarction in their right hemisphere. To be included, patients were required to: (1) have suffered a first-ever ischemic stroke involving the middle cerebral artery territory, as revealed by computed tomography, resulting in hemiparesis; (2) have a Fugl-Meyer (Assessment of Sensorimotor Recovery After Stroke scale) score in the motor subsection below 34;[31] (3) have the ability to walk, with close supervision if necessary, but without physical assistance as judged by the treating physiotherapist; (4) have the ability to stand with feet apart for 30 seconds or more; and (5) have provided written or verbal informed consent. Patients were excluded for one or more of the following reasons: (1) cognitive deficit that could hinder communication and cooperation (score below 24 in the Mini-Mental State Examination); (2) history of orthopaedic or neurological (other than stroke) disorders, known to affect walking performance and quiet standing position; (3) history of stroke involving the brainstem or cerebellar areas; and (4) taking medication such has antispasticity medication that could affect motor performance and balance. Gait data of post-stroke participants were compared with data obtained from the 23 healthy control participants. All participants in the control group were sedentary and were selected according to the same exclusion criteria which were applied to the post-stroke group; they were excluded if they had suffered any neurological disorder. Participants were considered sedentary if their practice of physical activities was less than three times per week during 20 minutes of continuous vigorous physical activities or less than 5 times per week during 30 minutes of continuous or intermittent moderate physical activities for at least the last 2 years. The study was approved by the local ethics committee and implemented according to the Declaration of Helsinki.

Instrumentation

The values of the vertical (F_z), anterior-posterior (F_x) and medial-lateral (F_y) components of the ground reaction force, as well as the values of the moments of force in the frontal (My) and sagital (Mx) planes, were acquired using a force plate[a] at a sampling rate of 1000Hz (FP4060-08 model from Bertec Corporation (USA), connected to a Bertec AM 6300 amplifier [a] and to an analogue board [b], from Qualysis, Inc. (Sweden)).

The force plate signals were analysed with the Acqknowledge software (Biopac Systems, Inc., USA).

Procedures

Data acquisition

All participants used their own regular footwear (1.5cm heel) while standing on a force plate, with feet at pelvis width and with their arms by their sides. They were asked to stand as still as possible and to focus on a target 2 meters away and at eye level for 30 seconds. After this, participants were asked to walk at self-selected speed over a 5 m walkway, without explicit instructions. If a subject asked which leg to start with, the researcher replied ‘‘whatever feels natural for you,’’ as lower limb preference plays an influential role in the control of frontal plane body motion during gait initiation.[32] However, participants were asked to keep the starting leg consistent over all trials. A trial was considered valid when the subject performed at least three steps. Each subject performed three trials with rest periods of 60 seconds between each trial, when the subjects remained seated. Before data acquisition, sufficient time was given so that the participants became familiar with the experimental settings.

Data processing

Ground reaction force signals were low-pass filtered using a fourth-ordered Butterworth filter by using a zero-phase lag with a cut-off frequency of 20 Hz. The acquired force and moment of force-time series of each trial were used to calculate the CoP fluctuation in the anterior-posterior (AP) and medial-lateral (ML) directions using the following approximations:

$$\mathrm{CoP_{AP}} = \frac{\mathrm{M_y}}{\mathrm{F_z}}, \qquad (1)$$

$$CoP_{ML} = \frac{M_x}{F_z} \quad (2)$$

CoP displacement in AP and ML directions, during the postural phase of gait initiation, was calculated using the difference between maximum CoP backward (first inflection of CoP_{AP}) and toward the swing limb (first inflection of CoP_{ML}) positions and the CoP position associated to the beginning of its displacement for each direction, respectively (Figure 1). Two methods were used to identify the beginning of CoP displacement: (1) a baseline-based method and (2) a maximal displacement based method. In both methods, identification was achieved using a computer program and visual inspection.

Baseline-based method

The mean of peak-to-peak amplitude and the dispersion time series estimated by standard deviation (SD) of CoP displacement were calculated for the ML and AP directions from 5 to 25 seconds of upright quiet standing. The mean plus 3 times the SD was defined as the threshold for gait initiation onset. The CoP position at the beginning of its displacement backward and towards the swing limb was assessed at the beginning of an interval lasting for at least 50 ms when its absolute value was higher than the threshold (Figure 1).[15] Only changes of CoP displacement with a minimum duration of 50 ms were considered, to exclude variations that are not related to gait initiation, as this interval corresponds to the electromechanical delay.[33]

Maximal displacement based method

The CoP position in AP and ML directions was assessed at the beginning of the interval lasting at least 50 ms, when its value was higher than 5% of the magnitude of the first inflection of CoP_{AP} displacement and of the magnitude of the first inflection of CoP_{ML} displacement, respectively (Figure 1).[15]

The threshold's selection was adapted from methods used on previous studies that have used the same criterion for other biomechanical variables, and on the fact that it provided a good agreement with visual inspection.[21,22,34]

Statistical analysis

The acquired data were analysed using the Statistic Package Social Science (SPSS)[c] software version 22, from *IBM Company* (USA). Reliability measures of CoP displacement assessed from each method were calculated for healthy (n=23) and post-stroke participants (n=15). The Intra-Class Correlation Coefficient ($ICC_{2,1}$) with a 95% Confidence Interval (CI) was used because it considers random effects over time and expresses relative reliability of the measures of CoP displacement obtained with each method. [23] Specifically, a two-way ANOVA model with a random subject effect was used to estimate the intra-session reliability. The following range of reliability coefficients were used to report the degree of reliability: 0.00 to 0.25 – little, if any correlation; 0.26 to 0.49 – low correlation; 0.50 to 0.69, moderate correlation; 0.70 to 0.89, high correlation and 0.90 to 1.00, very high correlation. [35] The Coefficient of Variation (CV) was used to express absolute reliability and was calculated per subject, by dividing SD by the mean of three trials.

Shapiro–Wilk test results and histogram analysis have shown that data were normally distributed. The statistical difference between ICCs was evaluated through the application of Fisher's Z transformation, with significance determined with the t statistic. The paired samples T-test was used to compare the CV, CoP displacement and postural phase duration values obtained with each method. The independent samples T-test was used to compare mean values of CoP displacement and CV values between healthy and post-stroke groups. Because of the reduced sample, the Wilcoxon test was used to compare CoP displacement between post-stroke participants that initiated gait with the ipsilesional limb, n=6 and those who initiated gait with the contralesional limb, n=9. Cohen's d was calculated to assess effect size and power analysis (1-β) was performed to give an indication of the power of hypothesis tests and the magnitude of the differences that researchers are able to detect in those settings. A 0.05 significance level was used for inferential analysis

Results

Higher reliability was obtained in CoP displacement values during the postural phase of gait initiation when using the baseline based method, in both healthy and post-stroke participants.

In healthy participants, when the baseline-based method was used, CoP displacement measures presented high to very high correlation, while values obtained with the maximal displacement based method presented high correlation (Table 2). Despite a tendency to lower values of ICC in the maximal displacement based method, no significant differences were observed (CoP_{AP}, p=.104; CoP_{ML}, p=.164). When analyzing CV values, statistically significant differences between methods occurred in both CoP_{AP} (p=.001, (1-β)=.99, Cohen´s *d*=1.11) and CoP_{ML} (p=.005, (1-β)=.45, Cohen´s *d*=.37), with higher values in the maximal displacement based method (Table 2).

In post-stroke participants, CoP displacement calculated using the baseline-based method presented high to very high intra-session correlation values, while moderate to high intra-session correlation values were obtained using the maximal displacement based method. However, there were no significant differences (CoP_{AP}, p=.278; CoP_{ML}, p=.194). The differences in reliability between the methods were more pronounced in

CV values, as higher values were observed in CoP_{AP} displacement (p=.007, (1-β)=.99, Cohen´s d=1.24) in the maximal displacement based method (Table 2).

Generally, CoP displacement was lower in post-stroke participants when compared to healthy participants (Table 2). Specifically, the post-stroke group presented lower CoP displacement backwards (p=.031) and towards the first swing limb (p=.001) when the baseline-based method was used. Despite decreased CoP displacement, post-stroke participants presented generally higher values of absolute variability (Table 2). When the maximal displacement based method was used, statistical differences were only observed in CoP_{AP} displacement (p=0.007) and higher absolute variability was observed in CoP_{AP} displacement (p=.004) in post-stroke subjects when compared to health participants (Table 2). No significant differences were observed in ICC values between healthy and post-stroke participants in both methods (Table 2).

Nine post-stroke participants initiated gait with their contralesional limb, while six initiated gait with their ipsilesional limb. Globally, a trend to decreased CoP displacement and increased absolute variability was observed in both limbs of post-stroke participants, when compared to healthy participants, in both methods (Figure 2). No differences were observed between post-stroke participants that initiated gait with ipsilesional and contralesional limbs in the baseline-based method (AP, p=.877, (1-β)=.13, Cohen´s d=.14; ML, p=.643, (1-β)=.09, Cohen´s d=.10) and in the maximal displacement based method (AP, p=.09, (1-β)=.34, Cohen´s d=.3; ML, p=.643, (1-β)=.18, Cohen´s d=.24).

When both methods were compared as to CoP displacement, significant differences were only observed in CoP displacement towards the first swing limb in subjects with stroke (p=0.039). Higher values were obtained using the maximal displacement based method (Table 2). In general, a trend to higher durations of postural phase were obtained with this method for CoP displacement towards the first swing limb (baseline-based method, 431±209ms (healthy), 563±281ms (post-stroke); maximal displacement based method, 504±196ms (healthy), 631±371ms (post-stroke)), while a trend to higher duration of postural phase was obtained for CoP backwards displacement using the baseline-based method (baseline-based method, 548±259ms (healthy), 618±252ms (post-stroke); maximal displacement based method, 366±187ms (healthy), 509±346ms (post-stroke)). Despite this tendency, statistically significant differences between methods were obtained for the duration of the postural phase in ML direction in subjects with stroke (p=0.028).

Discussion

Generally, both methods were reliable for identifying the postural control phase of gait initiation in healthy subjects. This low within-subject variability, associated with the non-significant differences observed between CoP displacement obtained with the two methods, demonstrates that both methods can be used to identify the postural phase of gait initiation in healthy participants. These high values of intra-session reliability are consistent with the evidence that the initiation of gait is accomplished by stereotyped patterns of activity and consequently stereotyped trajectory of CoP displacement.[3,4] However, the results obtained as to absolute reliability favour the use of the baseline-based method over the maximal displacement based method.

Higher differences between methods were obtained in post-stroke participants. Lower values of absolute variability were obtained with the baseline-based method associated with a trend to higher values of ICC, when compared to the maximal displacement based method. These findings seem to corroborate the high values of reliability for CoP displacement parameters obtained in upright standing in post-stroke subjects.[36,37] In fact, this has been demonstrated to occur despite the standing balance of post-stroke participants is characterised by increased CoP displacement and an asymmetrical weight bearing distribution in favour of the ipsilesional limb.[36,37]

It has been shown that increased CoP movements during quiet standing in post-stroke subjects seem partly related to increased body sway and partly to exaggerated corrective ankle mechanisms.[38,39] Based on this, it seems reasonable that the baseline-based method is associated with lower values of CoP displacement towards the first swing limb during the postural phase of gait initiation when compared to the maximal displacement based method. As there is higher CoP displacement during standing in post-stroke participants, the baseline standard deviation is higher. As a consequence, it takes longer to mark the onset of CoP displacement. In the present study, increased duration of the postural phase in ML direction was obtained in the post-stroke group when the maximal displacement based method was used. The greater the displacement of CoP in baseline, the lower will be the window of gait initiation extracted by the baseline method. As a consequence, CoP displacement values would be lower when compared to the maximal displacement method. In this case, the maximal displacement based method would possibly be more accurate to identify the CoP displacement towards the first swing limb onset as the baseline method is more influenced by the amount of sway during standing (baseline). In fact, when compared to healthy participants, different results have been obtained in post-stroke participants with each method. While lower CoP backwards displacement and lower CoP displacement towards the first swing limb was observed when the baseline-based method was used, no differences occurred in CoP_{ML} displacement with the maximal displacement based method. The differences between control and post-stroke groups as to CoP_{ML} displacement assessed with the baseline-based method may be caused by differences in baseline due to differences in body sway. However, the results obtained in the present study do not allow us to confirm this hypothesis.

Globally, the findings of the present study support the use of the baseline-based method to assess in a reliable way the onset of gait initiation. However, because the baseline method is more influenced by the amount of sway during standing, the maximal displacement based method seems to present greater sensitivity in identifying the beginning of CoP_{ML} displacement in post-stroke subjects. A higher variability of CoP_{ML} displacement during standing can explain the higher sensitivity of maximal displacement for detecting the beginning of CoP displacement towards the first swing limb. However, future studies are required to confirm this hypothesis.

The lower CoP displacement backwards and towards the first swing limb, observed in post-stroke participants, impairs posture stability and motor performance.[40] The decrease of CoP backward displacement during the postural phase leads to lower generation of forward momentum of the centre of mass and a consequent impairment of gait velocity and step length.[7,18] The dynamic stability is also compromised, as the reduction of CoP shift towards the swing-leg side increase the extent to which the centre of mass falls toward the swing-leg side during step execution, reducing the ML stability during gait initiation.[8,41]

The decreased backward CoP shift has been associated with a decreased inhibition of the soleus and the gastrocnemius and lower tibialis anterior activity associated with a delayed onset.[11,17] The dysfunction of the postural phase of the contralesional limb can result from tibialis anterior activation deficit as a consequence of affection of the lateral cortico-spinal system and from impairments in anticipatory postural adjustments as a result of a deregulation of supplementary motor area and premotor cortex. A deregulation of supplementary motor area and premotor cortex is typically found in post-stroke subjects showing damage in the territory of the middle cerebral area.[42-44] It should be noted that a lesion in the premotor cortex affects the anticipatory postural adjustments of bilateral lower extremities in step initiation.[43] Postural control dysfunction of the ipsilesional limb has been demonstrated in other functional tasks and particularly in participants with sub-cortical injuries located at the internal capsule level.[45-47] In fact, injuries located at this region are typically associated with dysfunction of the ventral–medial systems and may justify changes in the activity of the ipsilesional soleus muscle.[48] The neuronal connection of the soleus and the tibialis anterior need further discussion, but it can constitute a possible explanation to the dysfunction of the postural phase of gait initiation in the ipsilesional limb. Under this perspective, future research should attempt to investigate the activation patterns of ankle muscles during gait initiation of post-stroke participants.

The results obtained in this study indicate that both methods are reliable tools to assess the postural phase of gait initiation in healthy and post-stroke participants. Higher values of CoP displacements reliability were obtained with the baseline-based method. However, because the baseline method is more influenced by the amount of sway during standing, the maximal displacement based method seems to present greater sensitivity in identifying the beginning of CoP_{ML} displacement in post-stroke subjects. Both methods demonstrated that post-stroke participants present decreased CoP displacement during the postural phase of gait initiation. From a clinical point of view, these results indicate that attention should be given to the postural phase of gait initiation in the rehabilitation of post-stroke participants.

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Suppliers

a. Bertec Corp, 6171 Huntley Rd, Ste J, Columbus, OH 43229.

b. Qualysis AB, Packhusgatan 6, 411 13 Gothenburg, Sweden.

c. SPSS Inc, 233 S Wacker Dr, 11th Fl, Chicago, IL 60606.

Figure Captions

Figure 1: Representation of CoP displacement during the beginning of gait initiation with the right limb as first swing limb. The gray box in part a) represents an approximation of postural control phase of gait initiation. The onset of CoP displacement for AP and ML determinated by the baseline-based method (grey line) and the maximal displacement based method (dark line) are more precisely represented in part b). Dashed lines represent the threshold obtained with each method. The gray box in part b) represents postural control phase of gait initiation obtained by both methods.

Figure 2: Mean (bars) ± SD (error bars) of CoP displacement and CV obtained in ipsilesional and contralesional limbs of post-stroke subject and healthy controls during the postural phase of gait initiation with the baseline-based method and the maximal displacement based method.