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Correlations between measures of dynamic balance in individuals with post-stroke hemiparesis

Arian Vistamehr [a], Steven A. Kautz [b,c], Mark G. Bowden [b,c], Richard R. Neptune [d,*]

[a] Motion Analysis Center, Brooks Rehabilitation Hospital, Jacksonville, FL, USA
[b] Ralph H. Johnson VA Medical Center, Charleston, SC, USA
[c] Department of Health Sciences & Research and Division of Physical Therapy, Medical University of South Carolina, Charleston, SC, USA
[d] Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX, USA

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ABSTRACT

Mediolateral balance control during walking is a challenging task in post-stroke hemiparetic individuals. To detect and treat dynamic balance disorders, it is important to assess balance using reliable methods. The Berg Balance Scale (BBS), Dynamic Gait Index (DGI), margin-of-stability (MoS), and peak-to-peak range of angular-momentum (*H*) are some of the most commonly used measures to assess dynamic balance and fall risk in clinical and laboratory settings. However, it is not clear if these measures lead to similar conclusions. Thus, the purpose of this study was to assess dynamic balance in post-stroke hemiparetic individuals using BBS, DGI, MoS and the range of *H* and determine if these measure are correlated. BBS and DGI were collected from 19 individuals post-stroke. Additionally, kinematic and kinetic data were collected while the same individuals walked at their self-selected speed. MoS and the range of *H* were calculated in the mediolateral direction for each participant. Correlation analyses revealed moderate associations between all measures. Overall, a higher range of angular-momentum was associated with a higher MoS, wider step width and lower BBS and DGI scores, indicating poor balance control. Further, only the MoS from the paretic foot placement, but not the nonparetic foot, correlated with the other balance measures. Although moderate correlations existed between all the balance measures, these findings do not necessarily advocate the use of a single measure as each test may assess different constructs of dynamic balance. These findings have important implications for the use and interpretation of dynamic balance assessments.

1. Introduction

Balance control is a challenging task in many patient populations including individuals with post-stroke hemiparesis. More than 50% of stroke survivors experience falls within one year post-stroke (e.g., Ashburn et al., 2008). Lack of balance control can lead to physical injuries and long-term disabilities (e.g., Weerdesteyn et al., 2008). In addition, a recent study has shown that discordance was present between measured and perceived balance in over one third of the post-stroke individuals and that falls were more closely associated with measured balance than perceived balance (Liphart et al., 2015). Thus, it is important to assess dynamic balance using reliable methods in order to detect and treat balance disorders.

Various methods have been used to evaluate balance performance. These methods range from simple clinical scores such as Berg Balance Scale (BBS) (Berg et al., 1992) and Dynamic Gait Index (DGI) (Shumway-Cook and Woollacott, 1995) to more comprehensive laboratory-based measures such as margin-of-stability (MoS) (Hof et al., 2007) and whole-body angular momentum (*H*) (e.g., Silverman and Neptune, 2011). Further, clinical balance scores are based on discrete score assignments while completing a series of movement tasks, whereas the laboratory-based measures are continuous and obtained using kinematic and kinetic data during walking, often on a treadmill.

A survey study among 655 physical therapists has shown that BBS was the most commonly used measure to assess balance in stroke rehabilitation (Korner-Bitensky et al., 2006). A review study suggested that BBS is an effective and sound method for balance assessment in post-stroke individuals although a few studies observed floor and ceiling effects (Blum and Korner-Bitensky, 2008). Note that BBS is not a measure of dynamic balance, but is used through the use of a cut-off score (<42) that relates to a higher risk of falls (e.g., Tilson et al., 2012). Another clinical measure that is widely used for assessing dynamic balance during gait activities is DGI, which has shown high reliability and validity in

* Corresponding author. Tel.: +1 512 471 0848; fax: +1 512 471 8727.
E-mail address: rneptune@mail.utexas.edu (R.R. Neptune).

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ambulatory post-stroke individuals (Jonsdottir and Cattaneo, 2007). Similar to the BBS, the DGI utilizes a cut-off score of 19 to indicate increased risk of falls (Shumway-Cook et al., 1997; Wrisley and Kumar, 2010). However, others assessing dynamic balance in 117 patients with balance and vestibular disorders also reported ceiling effects, suggesting the need for assessments capable of measuring a broader range of gait abilities (Dye et al., 2013).

Margin-of-stability, a commonly used laboratory-based measure for assessing balance, is the minimum distance between the base of support and the extrapolated center-of-mass (CoM) (Hof, 2008). This measure is based on foot placement while accounting for body CoM position and velocity and has been used to assess dynamic balance in young healthy individuals in destabilizing environments (e.g., McAndrew Young et al., 2012), older adults while stepping to targets (Hurt and Grabiner, 2015), amputees (e.g., Bolger et al., 2014; Gates et al., 2013; Hof et al., 2007) and post-stroke individuals (e.g., Hak et al., 2013; Kao et al., 2014). Similarly, whole-body angular-momentum has been used to assess dynamic balance in a number of patient populations including post-stroke hemiparetic individuals (Nott et al., 2014), amputees (e.g., Pickle et al., 2014; Sheehan et al., 2015; Silverman and Neptune, 2011) and older adults (e.g., Pijnappels et al., 2005b). The regulation of whole-body angular-momentum is essential for maintaining dynamic balance during walking (e.g., Herr and Popovic, 2008) and can be achieved through proper foot placement and generation of appropriate ground-reaction-forces (GRFs) (e.g., Pijnappels et al., 2005a).

Prior studies have suggested that balance control in the mediolateral direction is more challenging than in the anterior-posterior direction and that active control is needed to regulate mediolateral balance (Bauby and Kuo, 2000). A recent study investigated the relationship between clinical balance scores and the time rate of change of frontal-plane H in post-stroke individuals and found that a higher rate of change of H during the paretic leg stance was associated with poorer BBS and DGI scores (Nott et al., 2014). However, no study to our knowledge has investigated whether assessment methods that include MoS provide consistent findings, implying a similar construct between measures, or whether different measures provide somewhat different information regarding dynamic balance in post-stroke individuals. Thus, the purpose of this study was to assess mediolateral balance using BBS, DGI, MoS and peak-to-peak range of H in post-stroke hemiparetic individuals and determine the strength and direction of the relationships between these variables.

2. Methods

Nineteen post-stroke hemiparetic individuals (14 left hemiparesis; age: 62 ± 11 years; 6 female) walked on a split-belt instrumented treadmill (Techmachine, Andrezieux Boutheon, France) at their self-selected walking speed (Table 1). Subject inclusion criteria were previously described in detail (Bowden et al., 2013). In summary, individuals experienced stroke within the past 6 months to 5 years of the data collection, had lower extremity hemiparesis and were able to walk at least 10 m with the assistance of maximum one person. The Fugl-Meyer Assessment scores of lower extremity motor recovery were less than 34 (Table 1). The study protocol and consent form were approved by an Institutional Review Board and all participants provided informed, written consent prior to study participation.

BBS and DGI data were collected for each participant according to standard procedures (Berg et al., 1992; Shumway-Cook and Woollacott, 1995). Three-dimensional kinematics were collected at 100 Hz using a 12-camera motion capture system (VICON, Los Angeles, USA) and GRFs were recorded at 2000 Hz while

Table 1
Participant characteristics: time since stroke, affected side, overground self-selected (SS) walking speed and lower extremity Fugl-Meyer (FMA) assessment score. The last row lists the mean values ($\pm$SD) across the participants. 'L' and 'R' indicate left and right, respectively.

Subject #	Months Since Stroke	Affected Side	SS Walking Speed (m/s)	Lower Extremity FMA
1	26	L	0.43	21
2	63	R	0.57	25
3	11	L	0.71	25
4	8	R	1.05	33
5	12	L	1.08	29
6	9	L	0.93	23
7	26	L	0.64	24
8	35	L	0.93	26
9	46	R	0.59	31
10	12	L	0.97	22
11	14	R	1.00	19
12	18	L	0.75	27
13	10	L	0.47	26
14	27	L	0.82	14
15	17	L	0.33	22
16	21	R	0.96	18
17	56	L	0.99	30
18	28	L	0.20	20
19	17	L	0.59	27
Mean($\pm$SD)	24($\pm$16)	–	0.74($\pm$0.27)	24.3($\pm$4.8)

participants walked at their self-selected walking speed during multiple 30-second trials (Bowden et al., 2013). The kinematic and GRF data were low pass filtered using a fourth-order Butterworth filter with cutoff frequencies of 6 Hz and 20 Hz, respectively. A 13-segment inverse dynamics model (C-Motion, Inc., Germantown, MD) was used to calculate body CoM position and velocity as well as angular-momentum for each segment. Center-of-pressure (CoP) was obtained using the force plates embedded in the treadmill. Margin-of-stability (MoS) in the mediolateral direction was calculated as the minimum distance between CoP and extrapolated center-of-mass (XcoM) (Hof et al., 2007). The XcoM was calculated as:

$$XcoM = Z + \frac{\dot{Z}}{\sqrt{\frac{l'}{g}}}$$

where Z and $\dot{Z}$ are the body CoM position and velocity, respectively. l' is the equivalent pendulum height (calculated as $1.34 \times$ leg length (Hof et al., 2007)) and g is the gravitational acceleration. MoS was calculated at each step for each foot placement and was normalized with respect to body height. In addition, to further understand MoS and its relationship to other measures, step width and step width variability (i.e., standard deviations normalized by body height) were calculated for each participant.

At each time step, whole-body angular-momentum (H) about the CoM was calculated as:

$$\vec{H} = \sum_{i=1}^{n} [(\vec{r}_i^{\,COM} - \vec{r}_{body}^{\,COM}) \times m_i(\vec{v}_i^{\,COM} - \vec{v}_{body}^{\,COM}) + I_i \vec{\omega_i}]$$

where $\vec{r}_i^{\,COM}$ and $\vec{v}_i^{\,COM}$ are the position and velocity vectors of the i-th segment's CoM, respectively. $\vec{r}_{body}^{\,COM}$ and $\vec{v}_{body}^{\,COM}$ are the position and velocity vectors of the whole-body CoM. $\vec{\omega_i}$, m_i and I_i are the angular velocity vector, and mass and moment of inertia of the i-th segment, respectively, and n is the number of segments. Angular-momentum was normalized by the product of subject mass, height and $\sqrt{g \cdot l}$, where g is the gravitational acceleration and l is the subject height. The term $\sqrt{g \cdot l}$ has units of m/s and is independent of walking speed. The peak-to-peak range of angular-momentum in the mediolateral direction was calculated as the difference