



Community-dwelling adults with a history of falling report lower perceived postural stability during a foam eyes closed test than non-fallers

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Abstract

Perceived postural stability has been reported to decrease as sway area increases on firm surfaces. However, changes in perceived stability under increasingly challenging conditions (e.g., removal of sensory inputs) and the relationship with sway area are not well characterized. Moreover, whether perceived stability varies as a function of age or history of falls is unknown. Here we investigate how perceived postural stability is related to sway area and whether this relationship varies as a function of age and fall history while vision and proprioceptive information are manipulated. Sway area was measured in 427 participants from the Baltimore Longitudinal Study of Aging while standing with eyes open and eyes closed on the floor and a foam cushion. Participants rated their stability [0 (completely unstable) to 10 (completely stable)] after each condition, and reported whether they had fallen in the past year. Perceived stability was negatively associated with sway area (cm²) such that individuals who swayed more felt less stable across all conditions ($\beta = -0.53$, $p < 0.001$). Perceived stability decreased with increasing age ($\beta = -0.019$, $p < 0.001$), independent of sway area. Fallers had a greater decline in perceived stability across conditions ($F = 2.76$, $p = 0.042$) compared to non-fallers, independent of sway area. Perceived postural stability declined as sway area increased during a multisensory balance test. A history of falling negatively impacts perceived postural stability when vision and proprioception are simultaneously challenged. Perceived postural stability may provide additional information useful for identifying individuals at risk of falls.

Keywords Postural sway · Perceived postural stability · Aging · Falls

Introduction

Individuals with balance problems often report feeling unsteady (Schieppati et al. 1999), although some individuals who report feeling unsteady appear to have normal sway during balance tests (e.g., persistent postural perceptual

dizziness, mal de débarquement syndrome) (Querner et al. 2000; Lewis 2004; Clark et al. 2013). This apparently normal sway may be facilitated by hypervigilance and co-contraction of leg muscles (Dieterich and Staab 2017), which are difficult to quantify in typical clinical settings. Perception of postural stability (i.e., “How stable did you feel?”) has previously been related to sway area during standing, such that as sway area increases, one’s subjective report of steadiness decreases (Schieppati et al. 1999). Sway area has been related to peripheral sensory function (Anson et al. 2017), which may directly influence perception of postural stability (Schieppati et al. 1999; Huffman et al. 2009; Naranjo et al. 2016). This is of particular relevance to older adults who experience age-related declines in multiple sensory systems (Black et al. 2008; Ko et al. 2015; Li et al. 2015). Indeed, postural sway has been suggested as an indicator of fall risk in older adults (Baczakowicz et al. 2008; Howcroft et al. 2017).

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Falls pose a significant public health risk that increases with age and negatively impacts the health and quality of life for the person who falls (Parry et al. 2014). Older adults with a history of falling often report being unsteady, are afraid/anxious of future falls, and report lower balance confidence (Maki et al. 1991; Delbaere et al. 2009; Parry et al. 2014). Past falls have an adverse effect on risk for future falls via increased fear of falling and changes in activity participation (Allison et al. 2013; Hoang et al. 2017). A history of falls or fear of falling may also bias perception of postural stability via an interaction between multisensory integration, affect, and cognition (Hull et al. 2013; Dieterich and Staab 2017).

It is not clear from previous studies how perception of postural stability is related to sway area when sensory information is systematically manipulated during balance testing. Increased cognitive demand (serial subtraction) does not influence perceived postural stability, but altering the size and shape of the base of support or closing the eyes reduced perceived postural stability (Tarantola et al. 1997; DiDomenico and Nussbaum 2005). Previous work has not included conditions that manipulate somatosensory reliability (such as standing on foam) or conditions where vestibular input would be the primary sensory contribution (such as standing on foam with eyes closed) (Shumway-Cook and Horak 1986; Agrawal et al. 2009). Perceived postural stability is thought to incorporate self-motion with internal representations of points of reference such as gravity or the size of the base of support (Cañal-Bruland et al. 2015), determined in part by sensory input. Given the decline in sensory function and perceptual thresholds with aging, it is important to determine how sensory balance challenges impact the relationship between perceived postural stability and sway area. Additionally, it is not known whether perceived stability differs based on a history of prior falls. Here we report on the relationship between sway area and perceived stability across four balance testing conditions when sensory information is systematically manipulated. We hypothesized that perceived postural stability would decrease as sway area increased as sensory information was systematically manipulated. Additionally, we hypothesized that a history of falling would be associated with a larger change in perceived stability, relative to sway area, as balance tasks became more challenging across conditions.

Methods

The Baltimore Longitudinal Study of Aging (BLSA) is an ongoing prospective cohort study initiated in 1958 and currently conducted by the Intramural Research Program of the National Institute on Aging (IRP-NIA). Subjects are community-dwelling participants aged 20 and older who undergo a standardized array of tests over 3 days every 1–4 years at

the Clinical Research Unit of the IRP-NIA in Baltimore, MD. The present analysis includes a cross-sectional sample of all BLSA participants seen between August 2014 and June 2016. During this time period 427 participants underwent postural sway testing and were also queried regarding their perceived postural stability (described below). Participants also completed testing with the Short Physical Performance Battery ($n=421$). All participants provided written informed consent. The BLSA study protocol was approved by the National Institute of Environmental Health Sciences Institutional Review Board. Demographic information was collected along with self-reported history of falling in the previous 12 months. A positive history of falling was defined as one or more falls in the previous 12 months. Participants were not eligible to participate in the postural testing if they could not stand and walk unassisted.

Postural sway and perceived stability

Center of mass (COM) sway area was measured using the BalanSens™ inertial measurement units including triaxial accelerometer, triaxial gyroscope, and a triaxial magnetometer (BioSensics LLC, Brookline, MA) placed at the waist and lower leg (Najafi et al. 2010). Body sway was recorded at 100 Hz and the BalanSens proprietary software calculated sway area based on the participants height and weight (Yalla et al. 2014). Each sensor provides quaternions that are converted to Euler angles in three dimensions. The Euler angles are converted to COM displacement using a two-segment model previously described in detail and validated by Najafi and colleagues (Najafi et al. 2010). COM displacement measured with the BalanSens was highly correlated ($r=0.92$) with center of pressure displacement (Najafi et al. 2010). Participants stood with feet together and hands on their hips, first on the floor with eyes open (FLEO, condition 1) and then with eyes closed (FLEC, condition 2) and then they stood on a foam cushion (Sunmate, Dynamic Systems, Inc.) of density 72.2 kg/m^3 first with eyes open (FOEO, condition 3) and then with eyes closed (FOEC, condition 4). Participants were provided up to three attempts to successfully complete one trial lasting 40 s for each condition (Wu et al. 2009; De Nunzio et al. 2014; Anson et al. 2017). Participants were progressed from condition 1 through 4, and in this cohort all participants were able to complete the first three conditions and progress to condition 4. Not all participants were able to successfully complete condition 4. After each balance test, participants were asked to rate how stable they felt using an integer scale from 0 (completely unstable) to 10 (perfectly stable) (Schieppati et al. 1999). Eleven point numeric rating scales, such as the one used here, have been widely used to characterize subjective phenomena in research and have high reliability and validity as reported in a recent review (Gries et al. 2017). Participants

were excluded from postural sway testing if they required assistance to stand from sitting or to walk to minimize the risk of falling during the balance testing. For each participant, the fitted slope between perceived postural stability and sway area was calculated for all successfully completed balance tests.

Short physical performance battery

Physical performance and mobility was assessed using the Short Physical Performance Battery (SPPB) which consists of standing balance tests, repeated chair stands, and a 6-m walk. Standing balance was assessed with, participants sequentially standing with their feet side-by-side, in semi-tandem, in full tandem, and then on one leg for 10 s each. Each balance task was recorded for 10 s whether the participant was successful at maintaining the prescribed position or not. For the chair stands, participants folded their arms across their chest and stand up once from a chair. If successful, they were instructed to stand up and sit down five times as quickly as possible, and the duration was recorded. Gait speed was calculated as the average of two repetitions of a usual pace 6-m walk with a standing start. Performance scores were based on a previously published scoring system with a maximum score of 12 (Guralnik et al. 1994). Individuals who score less than 10 have a higher risk of developing disability related to mobility and activities of daily living (Guralnik et al. 2000).

Data analysis

First, a multivariate mixed model regression was used to determine the relationship between perceived stability and sway area across balance conditions accounting for repeated testing within individuals. Perceived stability was modeled as the dependent variable and sway area, age, gender, and history of falling were independent variables. Second, descriptive statistics were calculated for the SPPB and a *t* test determined whether fallers and non-fallers differed in their SPPB scores. Third, an ANCOVA was used to determine whether sway area differed across conditions accounting for potential differences between fallers and non-fallers while controlling for perceived postural stability, age, and gender. Sway area was the dependent variable, postural condition, and status as a faller were independent variables, and covariates were perceived stability, age, and gender. Last, an ANCOVA was used to determine whether perceived postural stability differed across conditions accounting for potential differences between fallers and non-fallers while controlling for sway area, age, and gender. Perceived postural stability was the dependent variable, postural condition and status as a faller were independent variables, and covariates were sway area, age, and gender. The mixed model, *t* test,

and ANCOVA analyses were independent questions and main effects and interactions were considered statistically significant at $\alpha = 0.05$. A corrected $\alpha = 0.008$ was used for both ANCOVA analyses due to multiple planned post hoc comparisons.

Results

The mean age of the participants was 72.6 (SD 12.4, range 24–93) and 225 (52.7%) were women. The distribution of participants by decade was as follows: 13 adults under age 40, 17 aged 40–50, 21 aged 50–60, 96 aged 60–70, 148 aged 70–80, 122 aged 80–90, and 10 aged > 90. 92 participants (21.5%) reported at least one fall in the past year. The mean SPPB score was 11.6 (SD 0.95, range 6–12). There was not a significant difference between fallers and non-fallers on the SPPB [$t(1,423) = -0.0685, p = 0.4727$]. We used a multivariate mixed model regression to understand the contributions of the different factors on perceived postural stability (Table 1). Independent of the other factors, perceived postural stability was negatively correlated with sway area such that as sway area increased perceived postural stability decreased ($\beta = -0.53, p < 0.001$). This corresponds to a 0.53 point decrease in perceived postural stability for every 1 cm² increase in sway area. Including condition as a covariate in the regression model did not change the significance of the relationship between perceived postural stability and sway area (data not shown). Perceived postural stability also decreased with increasing age ($-0.019, p < 0.001$). This corresponds to a 0.2 point decrease in perceived postural stability for each decade, see Fig. 1. The relationship between perceived postural stability and sway area did not differ between fallers and non-fallers ($\beta = -0.17, p = 0.274$), see Fig. 2.

Table 1 Multivariate mixed regression model of predictors of perceived stability

Predictor variables	β	Standard error	95% CI
Age	-0.019 *	0.005	[-0.03, -0.009]
Gender			
Female	Ref	Ref	Ref
Male	-0.24	0.13	[-0.49, 0.02]
Sway area (cm ²)	-0.53*	0.02	[-0.57, -0.49]
History of falling			
Non-fallers	Ref	Ref	Ref
Fallers	-0.17	0.16	[-0.48, 0.13]
Intercept ^a	9.8		[9.05, 10.7]

β 's represent unstandardized regression coefficients. Significance indicated by *, p 's < 0.001

^aThe intercept would correspond to a male participant without a history of falling, age zero, and with sway area of 0 cm squared and thus is not interpreted

Overall, sway area increased significantly [$F(3,1690) = 302.9, p < 0.001$] across conditions as the balance tasks became progressively more difficult, and all pairwise comparisons were significant (p 's < 0.004), see Table 2. Perceived postural stability decreased across conditions [$F(3,1653) = 190.57, p < 0.001$]. Perception of postural

stability decreased statistically significantly in most, but not all pairwise comparisons across conditions as the balance task became progressively more difficult (p 's < 0.004), see Table 2. The exception was the progression from FLEO to FOEO where perceived postural stability was not significantly different between those conditions.

Fig. 1 Average perceived postural stability shown for each decade and balance test condition showing the decrease in perceived postural stability with increasing age. Error bars represent standard error of the mean

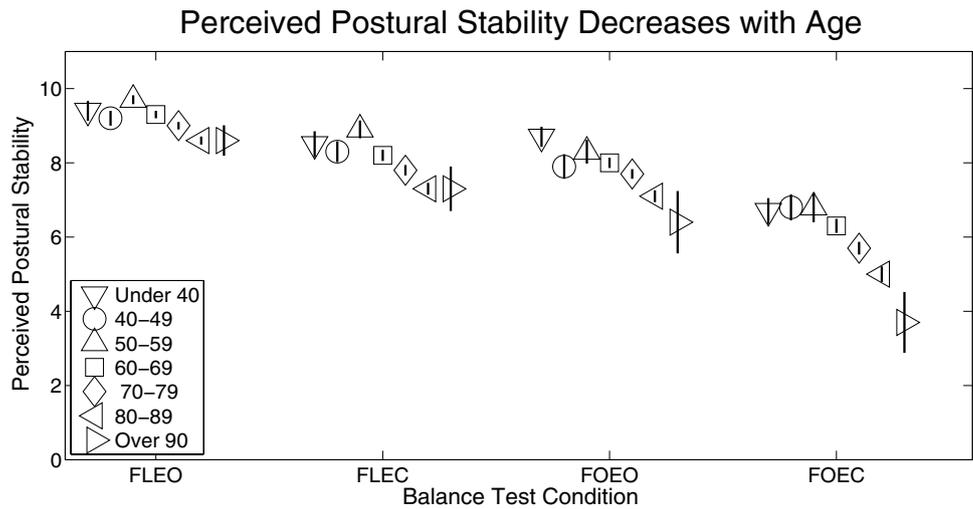


Fig. 2 Distribution of the slopes between perceived postural stability and sway area calculated for each participant

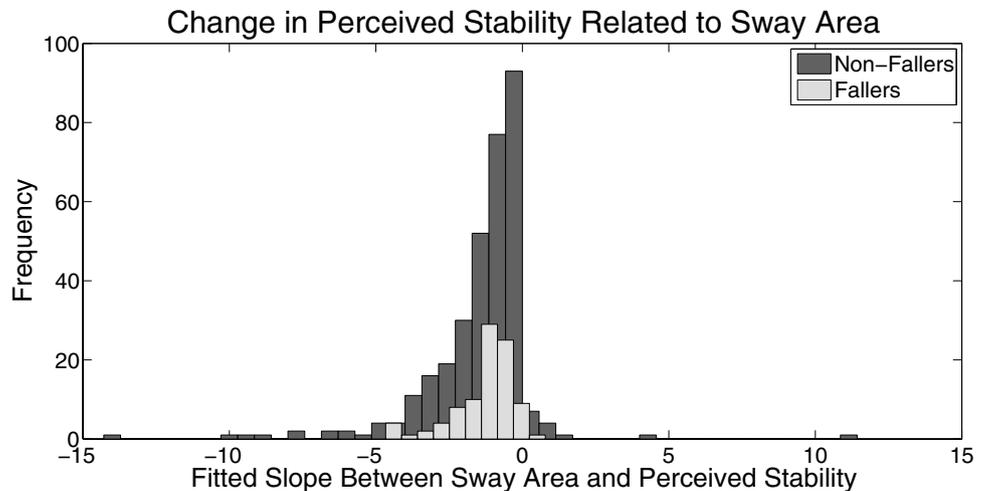


Table 2 Average (95% CI) COM sway area and perceived postural stability across balance test conditions

	FLEO	FLEC	FOEO	FLEC
COM sway, area (cm ²)	0.50 [0.47–0.55]	0.89* [0.80–0.97]	1.215*** [1.11–1.32]	3.24***,† [2.99–3.49]
Perceived postural stability	8.91 [8.74–9.07]	7.73 * [7.56–7.89]	7.55 * [7.39–7.71]	5.63 ***,† [5.47–5.79]

Average sway area and perceived postural stability was adjusted for model covariates (age, gender, and either perceived postural stability or sway area)

FLEO floor, eyes open, FLEC floor, eyes closed, FOEO foam, eyes open, FOEC foam, eyes closed

*Indicates significant change relative to FLEO

**Indicates significant change relative to FLEC

†Indicates significant change relative to FOEO. All significant comparisons p 's < 0.004

A history of falling was a significant covariate to the relationship between perceived stability and condition after controlling for sway area, age and gender. There was a steeper decline in perceived postural stability across conditions for fallers compared to individuals without falls indicated by an interaction between status as a faller and condition [$F(3,1653) = 2.74, p = 0.042$], see Fig. 3. This steeper decline in perceived stability across conditions was driven by the FOEC condition with fallers reporting significantly lower perceived postural stability ($t = -3.69, p = 0.006$). History of falling was not a significant covariate to the relationship between sway area and condition [$F(1,1653) = 1.65, p = 0.1986$] after controlling for perceived stability, age, and gender.

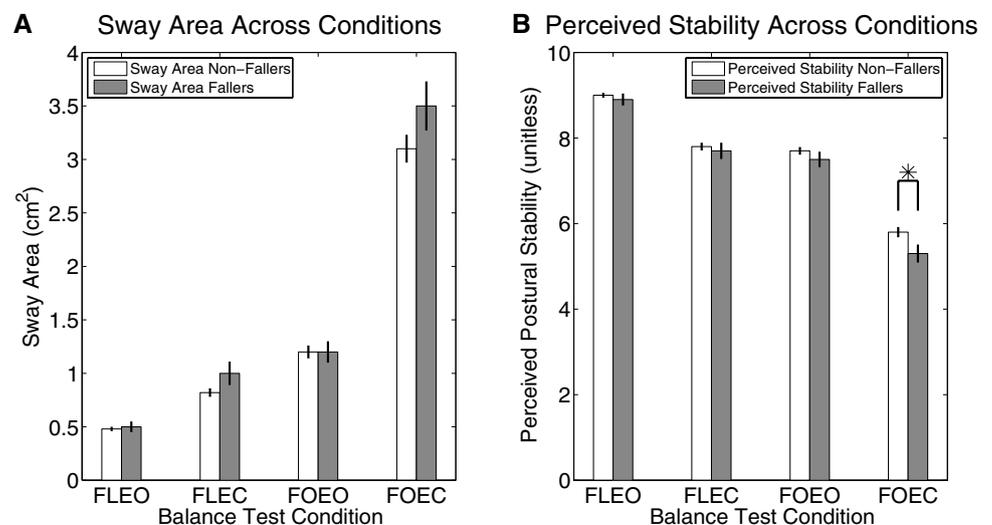
Discussion

Perceived postural stability decreased as sway area increased, extending results from prior studies on firm surfaces (Schieppati et al. 1999; DiDomenico and Nussbaum 2005; Murnaghan et al. 2009) to foam surfaces which offer additional sensory challenge. The current results add to prior work by including balance tests which manipulate somatosensory and visual sensory reliability encouraging increased reliance on vestibular inputs (Shumway-Cook and Horak 1986; Cohen et al. 1993). Interestingly, although all sensory manipulations resulted in a decrease in perceived postural stability compared to the FLEO condition, there was not a difference between FLEC and FOEO conditions. Perceived postural stability was equivalently impacted when only one sensory system was challenged regardless of which sensory modality (vision or proprioception) was challenged. In contrast, postural sway in the FOEO condition was significantly greater than during the FLEC condition. Medium and

high frequency sway increase when standing on foam with eyes open and closed (Fujimoto et al. 2014, 2015). Higher oscillation frequency may contribute to abnormal perception of stability for individuals who demonstrate elevated leg muscle co-contraction (Blaszczyk et al. 1993; Craig et al. 2017). Perceived stability has also been reported to decline as voluntary oscillation frequency increases (Martin Lorenzo and Vanrenstergem 2015). The difference in sway behavior and perception of postural stability could be explained by differences in multisensory integration.

These results suggest pathways for multisensory integration may differ between perception of postural stability and postural control. Perception of postural stability may depend more on the ability to represent one’s self, independent of the ability to represent external space, which has been shown to remain constant during balance tasks that systematically increase postural sway (Cañal-Bruland et al. 2015). For the balance task presented here, discrete processing of sensory input for perception and postural control may be less relevant since the available sensory input was always congruent with self-motion. However, discrete processing of sensory input for postural control and perception would be useful in more natural environments where optic flow can also result from object motion independent of postural sway (Gibson 1958). This would be particularly relevant in the context of obstacle avoidance, with important implications for multisensory processing during locomotion (Fajen and Warren 2003; Dokka et al. 2015). Alternatively, perceptual processing of self-motion may not be completely distinct from multisensory integration for postural control (Fitzpatrick and McCloskey 1994; Bacsı and Colebatch 2005). Dynamic sensory reweighting for postural control influences the perception of postural orientation between different body segments (Dalton et al. 2017). It remains to be demonstrated whether the relationship between perception of postural stability and

Fig. 3 Change in a sway area and b perceived postural stability across the rank ordered balance test conditions. Lighter bars represent non-fallers and darker bars represent fallers. Error bars represent standard error of the mean. * Denotes significant between group difference, note that this group difference was only present for perceived stability and only in the FOEC condition



postural control is bi-directional as has been reported to exist between motor planning and visual processing of relevant images (Bortoletto et al. 2011). Future studies are needed to investigate whether perceived postural stability directly or indirectly influences postural control.

In addition to the relationship between perceived postural stability and sway area, there was an independent relationship between perceived postural stability and age. As age increased, perceived postural stability decreased by 0.2 points for each decade, independent of sway area. Increased thresholds for detection of self-motion may contribute to the age-related decrease in perceived postural stability observed in this cohort. Older adults' perception of the onset of a fall is delayed relative to younger adults during temporal order discrimination tasks (what came first: falling or an auditory tone) (Lupo and Barnett-Cowan 2018). Perceived stability may be a construct that is influenced by both sensory integrity and contextual sensory perception. Vestibular perceptual thresholds of self-motion increase with age and higher thresholds were associated with balance problems on FOEC (Bermúdez Rey et al. 2016). Visual motion perception and proprioception thresholds also increase with age (Trick and Silverman 1991; Deshpande et al. 2003). Tremblay et al. previously reported no difference in perceived stability between young and older age groups (Tremblay et al. 2004). However, in contrast to the current study, Tremblay et al. excluded anyone with sensory changes or a history of falling thus limiting generalization to only the healthiest older adults. In our cohort there was considerable variability in perceived postural stability that increased with age. Task related anxiety (fear of falling) or cognitive impairments which impact sensory processing could also contribute to the relationship between age and perceived postural stability and future work is needed to identify how affect and cognitive ability impact perceived postural stability.

Clinical implications

It is interesting to note that several individuals in both the faller and non-faller groups had minimal to no change in perceived postural stability across the balance tasks, despite increase in sway (slopes approximately zero in Fig. 2). In contrast, individuals exposed to height-based postural threat report increased instability despite smaller or unchanged sway area (Huffman et al. 2009; Cleworth et al. 2012). The variability in perceptual response to changes in sway across conditions known to modulate postural control further demonstrates that all forms of postural threat are not created equal (Phanthanourak et al. 2016). Being able to match expected perception of self-motion to specific clinical testing conditions may be even more important for individuals with altered perception of self-motion, such as fallers.

Another novel contribution from this work is the characterization of the relationship between fall history and perception of postural stability. Individuals with a history of falling had a more negative change in perceived stability across conditions, driven by their lower perceived stability in the FOEC condition. A past fall could result in a persistent fear or anxiety response which negatively impacts perceived postural stability (Dieterich and Staab 2017). It is possible that the prior fall resulted in hypervigilance and the context of the balance testing paradigm increased the stress level of some participants (possibly via perceived threat) leading to a more negative perception of postural stability (Vaegter et al. 2018). Additionally, a prior fall may result in catastrophizing thoughts that bias perception in a negative way (Delbaere et al. 2009). Previous work demonstrated more diffuse cognitive processing for multisensory integration during standing balance in older adults, especially in the frontal–lateral brain region which facilitates attention (Lin et al. 2017). Fallers may allocate more attention to their postural sway during the FOEC balance task than non-fallers. Increased attention combined with hypervigilance could explain the more negative perception of postural stability in the group of fallers observed here. However, it is not clear whether the more negative perception of postural stability associated with a past fall is detrimental to the overall balance ability of the participants, especially since fallers and non-fallers did not differ in their physical performance or mobility as measured by the SPPB. An alternative interpretation is that the individuals with a less negative perception of postural stability over-estimate their stability. The effect of a prior fall may recalibrate perception with reality. In fact, the negative context of a prior fall may enhance processing of vestibular cues for both perception of postural stability and postural control (Preuss et al. 2015). Future studies are needed to determine the mechanisms which contribute to change in perceived postural stability, and to determine whether lack of change reflects a maladaptive perceptual behavior that leads to functional impairments such as falls.

Including measures of perceived postural instability with clinical examinations may offer added value especially since some traditional balance measures are less effective at identifying early changes in balance ability in older adults compared to reported instability (Tanaka et al. 2015). Balance training has beneficial effects on reducing postural sway both within a session (Tarantola et al. 1997), and after repeated training sessions targeting balance training (Rose and Clark 2000). Since the relationship between perception and action may be bi-directional (Bortoletto et al. 2011); it is important not only to ensure that as balance ability improves perception of stability also improves, but also to specifically address enhancing perception of postural stability. Balance confidence is often characterized in studies of balance, and it may be that a global perception of balance confidence

mediates the relationship between perception of stability and sway. Perception of postural stability is important to comprehensively evaluate balance ability in the context of rehabilitation.

Limitations

These data are cross-sectional and cannot be used to support causal inferences between the perceived postural stability and sway area. Fall history was determined by retrospective self-report and based on a single fall in the past year. Further, the mechanism linking fall history with steeper decline in perceived stability across balance conditions cannot be identified from this analysis. The population studied here are healthy adults and the relationship between postural sway and perception of postural stability may differ for individuals with more severe balance problems or sensory-motor pathology.

Conclusions

Perceived postural stability decreased as sway area increased across conditions of a multisensory balance test. A history of falling negatively impacts perceived postural stability specifically during standing balance testing on foam with eyes closed. Subjective perception of postural stability during balance testing may provide additional information useful for estimating fall risk.

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Compliance with ethical standards

Conflict of interest All other authors declare no conflict of interest.

Ethical approval All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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