Title
Contributions to lateral balance control in ambulatory older adults

Permalink
https://escholarship.org/uc/item/9br855jz

Journal
Aging Clinical and Experimental Research, 30(6)

ISSN
1594-0667

Authors
Sparto, Patrick J
Newman, AB
Simonsick, EM
et al.

Publication Date
2018-06-01

DOI
10.1007/s40520-017-0819-3

Peer reviewed

Published in final edited form as:

Aging Clin Exp Res. 2018 June ; 30(6): 633–641. doi:10.1007/s40520-017-0819-3.

Contributions to Lateral Balance Control in Ambulatory Older Adults

PJ Sparto[1], **AB Newman**[2], **EM Simonsick**[3], **P Caserotti**[4], **ES Strotmeyer**[2], **SB Kritchevsky**[5], **K Yaffe**[6], **C Rosano**[2], and **For the Health ABC Study**

[1]Department of Physical Therapy, University of Pittsburgh, Pittsburgh, PA

[2]Department of Epidemiology, University of Pittsburgh, Pittsburgh, PA

[3]Intramural Research Program, National Institute on Aging, Baltimore, MD

[4]Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark

[5]Department of Internal Medicine – Gerontology and Geriatrics, Wake Forest University, Winston-Salem, NC

[6]Department of Psychiatry, University of California San Francisco, San Francisco, CA

Abstract

Background—In older adults, impaired control of standing balance in the lateral direction is associated with increased risk of falling. Assessing the factors that contribute to impaired standing balance control may identify areas to address to reduce falls risk.

Aim—To investigate the contributions of physiological factors to standing lateral balance control.

Methods—Two hundred twenty-two participants from the Pittsburgh site of the Health, Aging and Body Composition Study had lateral balance control assessed using a clinical sensory integration balance test (standing on level and foam surface with eyes open and closed) and a lateral center of pressure tracking test using visual feedback. The center of pressure was recorded from a force platform. Multiple linear regression models examined contributors of lateral control of balance performance, including concurrently measured tests of lower extremity sensation, knee extensor strength, executive function, and clinical balance tests. Models were adjusted for age, body mass index, and sex.

Corresponding Author Contact Info: Patrick Sparto, PT, PhD, Department of Physical Therapy, Suite 210 Bridgeside Point, University of Pittsburgh, Pittsburgh, PA 15219, psparto@pitt.edu, P: 412-647-8069, F: 412-647-0108.

Disclosure of Potential Conflicts of Interest: The authors have no conflicts.

Research involving Human Participants and/or Animals: All procedures performed in studies 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.

Informed Consent: Informed consent was obtained from all individual participants included in the study

Author Contributions: Study concept and design (**PJS, ABN, EMS, PC, ESS, SBK, KY, CR**), acquisition of subjects and/or data (**PJS, ABN, EMS, PC, ESS, SBK, KY, CR**), analysis and interpretation of data (**PJS, ABN, EMS, PC, ESS, SBK, KY, CR**), and preparation of manuscript (**PJS, ABN, EMS, PC, ESS, SBK, KY, CR**).

Results—Larger lateral sway during the sensory integration test performed on foam was associated with longer repeated chair stands time. During the lateral center of pressure tracking task, the error in tracking increased at higher frequencies; greater error was associated with worse executive function. The relationship between sway performance and physical and cognitive function differed between women and men.

Discussion—Contributors to control of lateral balance were task-dependent. Lateral standing performance on an unstable surface may be more dependent upon general lower extremity strength, whereas visual tracking performance may be more dependent upon cognitive factors.

Conclusions—Lateral balance control in ambulatory older adults is associated with deficits in strength and executive function.

Keywords

Aging; Balance; Visual Feedback; Posturography; Executive Function

Introduction

Much investigation has been devoted to understanding what factors contribute to falls and imbalance leading to falls.[1] In particular, multifactorial examinations of large cohorts have been useful because of their ability to extract the most important risk factors while accounting for important covariates.[2] Nonetheless, we continue to lack a clear understanding of how these risk factors relate to the mechanisms of falling.

Impaired standing balance is one of several components of balance that has been related to falls, especially in the medio-lateral direction.[3,4] Assessment of the physiological factors that contribute to impaired standing balance control may identify overlooked areas to address to reduce falls risk. For example, age-related changes in somatosensation,[5,6] vision,[7] and vestibular function[8] have been related to poor balance and increased fall risk. Reduced lower extremity muscle strength and power have been associated with impaired balance as well.[9,4,10] Recently, executive dysfunction has been related to impaired mobility in terms of reduced gait speed and balance performance.[11–13]

Assessment of balance requires the evaluation of many different domains, including biomechanical factors, responses to internal and external perturbations, and walking control.[14] One of the domains that has been studied most frequently is the sensory control of standing balance, which involves coordination of sensory inputs (i.e. vision, lower extremity somatosensation, and vestibular sensation), and their integration in the central nervous system to produce an appropriate motor response. Aging has a definitive negative impact on performance of these tests.[8,15], but the large majority of these studies have utilized older adults less than 80 years.[16,17,8] The current investigation provides important information about this balance domain in large sample of adults with a mean age of 85.

Another balance domain that has been assessed involves the ability to control movement of the body through weight shifting. Frequently this has been assessed by recording a person’s maximum excursion in the anterior-posterior or medial-lateral directions. Other studies have measured the ability to control the weight shifting by having participants track a target using visual feedback.[18–21] These tests have shown an age-related effect of decrease in maximum excursion and worse performance on the tracking tasks in older adults.[21,18] Because impaired control of balance has an association with falls risk, it is important to discover what other physiological factors relate to this control.[3]

The purpose of this study was to investigate the contributions of physiological factors on standing balance control, using a standard test of sensory balance control as well as a novel visual feedback test of controlling lateral weight shifting. We hypothesized that the contributors to the two types of standing balance control would differ, such that a tracking task would engage cognitive factors, and the sensory test would involve sensorimotor factors.

Methods

Participants

Participants consisted of 222 men and women (55% female; mean age 85±SD 3 years, 43% Black) with postural control data from the Healthy Brain Project (HBP), an ancillary study to the Health, Aging and Body Composition (Health ABC) Study. The Health ABC study is a longitudinal cohort study of black and white, initially well-functioning, community dwelling older men and women from Pittsburgh, PA and Memphis, TN (n=3075; age 70-79; 48.4% male; 41.6% Black at baseline in 1997-98) that originated in 1997 to examine relationships between body composition and other health measures related to incident functional limitations and disability. Participants were recruited via mailings to a random sample of white Medicare beneficiaries and to all age-eligible black Medicare beneficiaries as well as community residents. Eligibility criteria included: no self-reported difficulty in walking ¼ mile, climbing 10 steps, or performing any basic activity of daily living; no life-threatening cancers; and plans to remain in the study area for at least the next three years. The study protocol was approved by the University of Pittsburgh and all participants provided informed consent. The population has been described elsewhere.[22]

Procedures

Lower extremity sensory function was assessed by testing vibration sense, pressure sensation, and pin-prick sensation. Knee extensor isometric strength was measured using a dynamometer (Kin-Com, model 125 AP,Chattanooga, TN) with a maximum effort for 5 seconds. Peak and average torque during this time was recorded as described elsewhere.[23] The Modified Mini-Mental State examination was administered in order to characterize the general cognitive functioning of the sample.[24]

Three pen and paper measures of executive function were administered: the Digit Symbol Substitution Test (DSST, number of symbols completed in 90 s),[25] the 15-item Executive Interview (EXIT 15, score 0-30 with 0 best, adapted from the EXIT 25 for the Health ABC study),[26] and the Executive Clock Drawing Task (CLOX 1, score 0-15 with 15 best).[27] Executive function performance is reported in Table 1.

The Short Physical Performance Battery (SPPB) was developed as a measure of physical performance for a longitudinal study of aging conducted by the National Institutes on Aging.

[28] Included in the SPPB are gait speed over 6 m, timed chair stands, and standing with different bases of support. Eleven percent of the participants were not able to perform the timed chair stands, and 19% were not able to complete the entire SPPB. The performance of the timed chair stands and gait speed subtests and total score of the SPPB are also reported in Table 1.

Sensory Control of Standing Balance Test

The test of standing balance was based on the original Clinical Test of Sensory Interaction on Balance,[29,30] which was designed to assess how people utilize the three most important sensory modalities for balance. Thus, the test assesses use of vision, somatosensation and peripheral vestibular sensation in 4 test conditions: eyes open and eyes closed on a stable surface (a force platform), and eyes open and eyes closed on a compliant surface (a 7.5 cm thick medium-density foam pad). The participants stood upright with feet together, for as long as they could up to a maximum of 30 seconds or until they lost their balance or took a step. Participants wore a safety harness and were guarded by a research technician. Ground reaction forces were recorded from the force platform (Bertec Corp) using Labview software (National Instruments, Inc.), and the root mean square (RMS) of the center of pressure (COP) in the antero-posterior (AP) and medio-lateral (ML) directions was computed for trials that lasted at least 15 s. The RMS of the COP is a measure of the variability of displacements of the COP and represents the overall power in the signal. Although more sophisticated measures are available, the RMS was chosen due to its ease of interpretation.

Lateral Center of Pressure Tracking Test

Participants performed a postural control test in which they controlled the movement of their medio-lateral center of pressure (ML COP) using visual feedback (Figure 1). The reason for concentrating on lateral step behaviors is that the control of postural reactions in the lateral direction appears to be related more to a history of falling than control in the anterior-posterior direction.[3] In addition, the visual feedback task will engage cognitive resources that may provide greater information about the health of the conscious postural control system. Subjects stood on the force platform with their feet 16 cm apart. On a computer monitor approximately 1.5 m in front of the subjects, an open circle moved back and forth along a horizontal line. In addition, an “X” that represented the subject’s ML COP was displayed on the same horizontal line. Subjects were instructed to keep the “X” inside the open circle. Four trials of 60 s duration were performed in which the circle moved sinusoidally at 0.25 Hz, a frequency close to the RMS of the COP during quiet stance in older adults. Additionally, frequencies of 0.125 Hz, 0.5 Hz, and 0.75 Hz were added, with four trials of 60s duration each. These frequencies were chosen because they span the range of frequency of typical spontaneous sway.[31] The order of the trials was from the slowest (0.125Hz) to the fastest (0.75Hz) of the frequencies of target’s movements. The target’s movement was scaled to a range of 16 cm, so that during slow movements, participants would be shifting their weight from one foot to the other while keeping both feet in contact with the platform. The RMS error between the position of the target and the ML COP was computed.

Statistical Analysis

Chi-square tests were used to examine the association between demographic variables (age, sex, body mass index) and performance during the sensory control and lateral COP tracking tests. A repeated measures ANOVA tested for the effect of static standing balance condition on the RMS ML COP, and the effect of frequency of the tracking task (e.g. the speed of movement of the target) on the RMS error, respectively. Post-hoc analysis of significant effects was conducted using Sidak correction for multiple comparisons. A significance level of $\alpha = 0.05$ was used.

Multiple linear regression was used to examine the contribution of measures of sensation, strength, and cognition to medial-lateral balance performance. The dependent variables were the z-scores of the RMS COP of quiet stance on foam with eyes open, and RMS error during the lateral tracking task at 0.25 Hz. An initial model was constructed by entering age, sex and body mass index. Then three additional models were evaluated by independently examining the contribution of: 1) sensation (i.e. the presence of any abnormal sensation test), 2) strength (timed performance of 5 chair stands, and peak knee extension torque), and 3) cognition (DSST, EXIT15, and CLOX1 performance). For the strength and cognition models, the variables were entered stepwise, using $p < 0.05$ as the entrance criterion. Additional models were constructed stratified by sex when sex was a significant factor in the regression.

Results

Sensory Control of Standing Balance

The ability to complete the sensory control test was strongly affected by visual input and surface support conditions. Ninety-four and 95% of the subjects were able to stand for at least 15 seconds on a level surface with eyes open and closed. When standing on foam, the percent of subjects who could complete at least 15 seconds dropped to 78% with eyes open and 44% with eyes closed. Factors that were associated with inability to stand for at least 15 s on foam with eyes closed included any abnormal lower extremity sensation test result ($p = 0.002$), higher BMI ($p = 0.034$), worse performance on the DSST ($p = 0.003$), slower repeated chair stands ($p = 0.002$), slower gait speed ($p = 0.013$), and lower SPPB score ($p = 0.001$).

Similarly, the RMS of the ML COP was significantly influenced by the visual input and surface support conditions ($p < 0.001$, Figure 2). While no difference in RMS COP was detected between the eyes open and eyes closed conditions on a level surface (pairwise $p = 0.90$), the RMS COP increased significantly when performed on the foam surface with eyes open (pairwise $p < 0.001$ vs. level surface conditions), and even more with eyes closed on the foam (pairwise $p < 0.001$ vs. all other conditions).

We only include results of the multiple linear regression related to performance during the foam, eyes open condition because it produced significantly greater sway than the level surface condition, and was not as affected by subjects not completing the tests as compared with the foam, eyes closed condition. Age, sex and BMI explained 12% of the variance in performance on the foam, eyes open condition. Of the three predictor variables in the initial model, age was not associated with RMS COP, but men produced greater RMS COP than women, and greater sway was related to greater BMI. To this initial model, there was no additional contribution of abnormal sensation, knee extensor strength, or cognition. However, timed chair stands explained an additional 10% of the variance in performance ($\beta = 0.306$, $p < 0.001$, Table 2). Slower performance on the repeated chair stands was associated with larger RMS of the COP (e.g. greater sway) while standing on foam with eyes open, independent of age, sex and BMI. Because sex was a significant predictor of performance, the regression analysis was stratified by sex (Table 2). These subgroup analyses showed that the relationship between timed chair stands and sway was greater in women compared with men. Furthermore, unexpectedly, greater peak knee extensor strength in women was associated with greater sway.

Lateral Center of Pressure Tracking Test

Between 87% and 92% of the participants were able to successfully perform the pressure tracking test across the frequencies of target movement. An example of two subjects' ability to perform the task is illustrated in Figure 3. The first subject was able to track the target with accurate amplitude and timing (Figure 3a), whereas the second subject had errors in both amplitude and timing (Figure 3b). The size of the RMS error (e.g. difference between the target position and COP) increased with faster frequency of target movement (Figure 4, $p < 0.001$). Post-hoc analysis revealed that the RMS error increased significantly at each successive frequency, from 3.3 cm at 0.125 Hz, 3.9 cm at 0.25Hz, 6.2 cm at 0.50 Hz and 6.8 cm at 0.75 Hz. The size of error in tracking task was not associated with the magnitude of RMS COP during the sensory control tests.

We first present results for the trials with the 0.25 Hz lateral tracking task because it had the greatest amount of variance explained by the predictor variables (Table 3). Age, sex and BMI explained 16% of the variance in the target tracking performance. Of the three predictor variables in the initial model, only sex was significantly associated with tracking performance, with females having greater error than males. Abnormal sensation and strength did not provide any additional information to the variance in tracking error. Greater RMS error was related to worse performance on the DSST ($\beta = -0.213$, $p = 0.002$), explaining an additional 4% variance, independent of age, BMI and sex. Since sex was a significant predictor of performance, the regression analysis was again stratified by sex (Table 3). In men, the association between DSST performance and error in tracking performance was not significant, perhaps as a result of smaller sample size. However, in women, a significant association between DSST and lateral tracking error was found, and explained 7% additional variance.

Associations of RMS error at the slower (0.125 Hz) and faster (0.50, and 0.75 Hz) frequencies with the predictor variables resulted in lower amount of variance explained compared to the model at 0.25 Hz. At 0.5 Hz, worse performance on the DSST was a significant predictor of greater RMS error ($\beta = -0.173$, $p = 0.019$) independent of age, BMI and sex. Finally, at 0.75 Hz, worse performance on the EXIT 15 was a significant predictor of greater RMS error ($\beta = 0.272$, $t = 3.79$, $p < 0.001$), independent of age, BMI and sex.

Discussion

We observed greater variability in center of pressure during the conditions of eye closure and on foam, which is typical of most studies that assess sensory contributions to balance control.[16,17] The larger increase in sway during stance on foam compared with closing the eyes suggests that older adults rely more on somatosensation for balance control compared with vision.[32]

We also investigated control of balance using a visual feedback center of pressure tracking task, which engaged cognitive resources other than the relatively automatic postural responses assessed in the sensory control of standing balance task. The RMS error between the target and the center of pressure increased as frequency increased. Additional analysis of the center of pressure revealed that the increase in error was due to a combination of reduced amplitude of movements at the 0.5 and 0.75 Hz tracking frequencies, and an increased phase lag between the target and center of pressure as the frequency increased. Although the increase in error has not been demonstrated in postural tracking tasks before, it has been demonstrated in a manual tracking task.[33]

Other research studies have examined the performance of weight shifting using visual feedback as a method for assessing balance control. For example, Lord et al (1996) discovered that greater errors in this balance performance were related to strength and reaction time, but it is important to note that sensation was not measured.[20] Cofre-Lizama et al. developed a center of mass tracking task in the medial-lateral direction that assessed performance across a range of frequencies from 0.1 to 2.0 Hz.[18] Healthy older adults had reduced amplitude and greater phase lag compared with young adults, suggesting that older adults would have had increased error in performance.[18] Yeh et al. examined the effect of age on performance of a center of pressure tracking task and discovered worse performance in older adults, that was amplified when delays in visual feedback were increased.[21]

We used multiple linear regression to examine the contribution of intrinsic factors of sensation, strength and cognition to performance on the static standing and lateral tracking control task. The primary contributor to the sensory control of standing task after adjusting for the demographic factors, was performance on the repeated chair stands test. Worse performance on the repeated chair stands test was also related to inability to maintain stance on foam with eyes closed. The relationship between control of sway and repeated chair stands has also been observed by Lord et al. (2002).[34] Performance on the repeated chair stands test is considered to be a proxy measure of lower extremity strength, but also involves significant postural control requirements.[35,34]

The most important contributor to the lateral COP tracking task was the Digit Symbol Substitution Test, suggesting that the visual feedback control task is indeed tapping into some of the same cognitive resources as executive function tasks. The DSST has been a considered to be a general test of cognitive processing speed.[36] Visuomotor coordination and selective attention are some of the important factors that determine the final score. The ability to filter out irrelevant information (e.g., symbols that may look alike) also influences performance. We believe that the DSST had a greater association with the visual feedback control task compared with the EXIT15 and CLOX 1 because the latter two tests are assessing a diverse array of executive control functions that are not necessarily involving timing of responses or visuospatial attention. Thus it does not appear that global executive function control is needed to control rhythmic weight shifting.

Conclusion

In older adults with an average age of 85 years, the control of lateral sway in both quiet standing and a postural tracking task was found to be related to timed chair standing performance and cognitive processing speed, respectively. Consequently, a clinical recommendation to improve the sensory control of standing balance may be the addition of a lower extremity strength training program. Furthermore, the significant effect of sex on the sway performance during quiet standing may indicate that strength is a more critical determinant of standing balance ability in older women compared with older men, and thus resistance exercises may be an important component of balance training in women. Assessment of cognitive processing speed may be a simple way of determining how well a person can control their lateral weight shifting abilities, which is important for transferring. A limitation of this study is that not all balance domains, cognitive or physiological factors could be assessed due to time constraints; thus, other factors may be important contributors for balance function.

Acknowledgments

This research was supported by National Institute on Aging (NIA) Contracts N01-AG-6-2101; N01-AG-6-2103; N01-AG-6-2106; and grants P30-AG024827, K23-AG028966 (CR), R01-AG029232 (CR), and R01-AG028050 (ESS). This research was supported in part by the Intramural Research Program of the NIH, National Institute on Aging.

The authors would like to acknowledge the important work of the staff of the Medical Virtual Reality Center (James Cook, Rob Cavanaugh, Michelle Lin), the staff of the Healthy Brain Project (Jessica King, Anne Ritter, Mei Yang, and Ge Liu), for their assistance in programming, data collection, and data analysis. The authors would also like to thank Luigi Ferrucci, MD, PhD for his recommendations on the study.

Sponsor's Role: The sponsor provided guidance in study design, methods, subject recruitment, data collections, analysis and preparation of paper.

References

1. Panel on Prevention of Falls in Older Persons, American Geriatrics Society and British Geriatrics Society. Summary of the Updated American Geriatrics Society/British Geriatrics Society clinical practice guideline for prevention of falls in older persons. J Am Geriatr Soc. 2011; 59(1):148–157. [PubMed: 21226685]
2. Delbaere K, Close JC, Heim J, Sachdev PS, Brodaty H, Slavin MJ, Kochan NA, Lord SR. A multifactorial approach to understanding fall risk in older people. J Am Geriatr Soc. 2010; 58(9): 1679–1685. [PubMed: 20863327]
3. Maki BE, Holliday PJ, Topper AK. A prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. J Gerontol. 1994; 49(2):M72–84. [PubMed: 8126355]
4. Lord SR, Rogers MW, Howland A, Fitzpatrick R. Lateral stability, sensorimotor function and falls in older people. J Am Geriatr Soc. 1999; 47(9):1077–1081. [PubMed: 10484249]

5. Bergin PS, Bronstein AM, Murray NM, Sancovic S, Zeppenfeld DK. Body sway and vibration perception thresholds in normal aging and in patients with polyneuropathy. Journal of Neurology, Neurosurgery & Psychiatry. 1995; 58(3):335–340.
6. Lord SR, Ward JA, Williams P, Anstey KJ. Physiological factors associated with falls in older community-dwelling women. J Am Geriatr Soc. 1994; 42(10):1110–1117. [PubMed: 7930338]
7. Lord SR, Clark RD, Webster IW. Visual acuity and contrast sensitivity in relation to falls in an elderly population. Age Ageing. 1991; 20(3):175–181. [PubMed: 1853790]
8. Peterka RJ, Black FO. Age-related changes in human posture control: sensory organization tests. J Vestib Res. 1990; 1(1):73–85. [PubMed: 1670139]
9. Lord SR, Ward JA. Age-associated differences in sensori-motor function and balance in community dwelling women. Age Ageing. 1994; 23(6):452–460. [PubMed: 9231937]
10. Horlings CG, van Engelen BG, Allum JH, Bloem BR. A weak balance: the contribution of muscle weakness to postural instability and falls. Nature clinical practice Neurology. 2008; 4(9):504–515. DOI: 10.1038/ncpneuro0886
11. Atkinson HH, Rosano C, Simonsick EM, Williamson JD, Davis C, Ambrosius WT, Rapp SR, Cesari M, Newman AB, Harris TB, Rubin SM, Yaffe K, Satterfield S, Kritchevsky SB, Health ABCs. Cognitive function, gait speed decline, and comorbidities: the health, aging and body composition study. J Gerontol A Biol Sci Med Sci. 2007; 62(8):844–850. [PubMed: 17702875]
12. Rosano C, Simonsick EM, Harris TB, Kritchevsky SB, Brach J, Visser M, Yaffe K, Newman AB. Association between physical and cognitive function in healthy elderly: the health, aging and body composition study. Neuroepidemiology. 2005; 24(1-2):8–14. [PubMed: 15459503]
13. Rapport LJ, Hanks RA, Millis SR, Deshpande SA. Executive functioning and predictors of falls in the rehabilitation setting. Arch Phys Med Rehabil. 1998; 79(6):629–633. [PubMed: 9630140]
14. Horak FB, Wrisley DM, Frank J. The Balance Evaluation Systems Test (BESTest) to differentiate balance deficits. Phys Ther. 2009; 89(5):484–498. [PubMed: 19329772]
15. Gill J, Allum JH, Carpenter MG, Held-Ziolkowska M, Adkin AL, Honegger F, Pierchala K. Trunk sway measures of postural stability during clinical balance tests: effects of age. J Gerontol A Biol Sci Med Sci. 2001; 56(7):M438–447. [PubMed: 11445603]
16. Camicioli R, Panzer VP, Kaye J. Balance in the healthy elderly: posturography and clinical assessment. Arch Neurol. 1997; 54(8):976–981. [PubMed: 9267972]
17. Judge JO, King MB, Whipple R, Clive J, Wolfson LI. Dynamic balance in older persons: effects of reduced visual and proprioceptive input. J Gerontol A Biol Sci Med Sci. 1995; 50(5):M263–270. [PubMed: 7671028]
18. Cofre Lizama LE, Pijnappels M, Faber GH, Reeves PN, Verschueren SM, van Dieen JH. Age effects on mediolateral balance control. PLoS One. 2014; 9(10):e110757.doi: 10.1371/journal.pone.0110757 [PubMed: 25350846]
19. Krasilovsky G, Gianutsos J. Effect of video feedback on the performance of a weight shifting controlled tracking task in subjects with parkinsonism and neurologically intact individuals. Exp Neurol. 1991; 113(2):192–201. [PubMed: 1868902]
20. Lord SR, Ward JA, Williams P. Exercise effect on dynamic stability in older women: a randomized controlled trial. Arch Phys Med Rehabil. 1996; 77(3):232–236. [PubMed: 8600863]
21. Yeh TT, Cluff T, Balasubramaniam R. Visual reliance for balance control in older adults persists when visual information is disrupted by artificial feedback delays. PLoS One. 2014; 9(3):e91554.doi: 10.1371/journal.pone.0091554 [PubMed: 24614576]
22. Tian Q, Glynn NW, Erickson KI, Aizenstein HJ, Simonsick EM, Yaffe K, Harris TB, Kritchevsky SB, Boudreau RM, Newman AB, Lopez OL, Saxton J, Rosano C, Health ABCS. Objective measures of physical activity, white matter integrity and cognitive status in adults over age 80. Behav Brain Res. 2015; 284:51–57. DOI: 10.1016/j.bbr.2015.01.045 [PubMed: 25655514]
23. Goodpaster BH, Carlson CL, Visser M, Kelley DE, Scherzinger A, Harris TB, Stamm E, Newman AB. Attenuation of skeletal muscle and strength in the elderly: The Health ABC Study. J Appl Physiol (1985). 2001; 90(6):2157–2165. [PubMed: 11356778]
24. Teng EL, Chui HC. The Modified Mini-Mental State (3MS) examination. J Clin Psychiatry. 1987; 48(8):314–318. [PubMed: 3611032]
25. Wechsler Adult Intelligence Scale. Psychological Corporation; San Antonio, TX: Revised 1981

26. Royall DR, Mahurin RK, Gray KF. Bedside assessment of executive cognitive impairment: the executive interview. J Am Geriatr Soc. 1992; 40(12):1221–1226. [PubMed: 1447438]
27. Royall DR, Cordes JA, Polk M. CLOX: an executive clock drawing task. J Neurol Neurosurg Psychiatry. 1998; 64(5):588–594. [PubMed: 9598672]
28. Guralnik JM, Simonsick EM, Ferrucci L, Glynn RJ, Berkman LF, Blazer DG, Scherr PA, Wallace RB. A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. J Gerontol. 1994; 49(2):M85–94. [PubMed: 8126356]
29. Shumway-Cook A, Horak FB. Assessing the influence of sensory interaction on balance. Phys Ther. 1986; 66:1548–1550. [PubMed: 3763708]
30. Whitney SL, Wrisley DM. The influence of footwear on timed balance scores of the modified clinical test of sensory interaction and balance. Arch Phys Med Rehabil. 2004; 85(3):439–443. [PubMed: 15031830]
31. Lin D, Seol H, Nussbaum MA, Madigan ML. Reliability of COP-based postural sway measures and age-related differences. Gait Posture. 2008; 28(2):337–342. DOI: 10.1016/j.gaitpost.2008.01.005 [PubMed: 18316191]
32. Wiesmeier IK, Dalin D, Maurer C. Elderly Use Proprioception Rather than Visual and Vestibular Cues for Postural Motor Control. Frontiers in aging neuroscience. 2015; 7:97.doi: 10.3389/fnagi.2015.00097 [PubMed: 26157386]
33. Langenberg U, Hefter H, Kessler KR, Cooke JD. Sinusoidal forearm tracking with delayed visual feedback. I. Dependence of the tracking error on the relative delay. Exp Brain Res. 1998; 118(2):161–170. [PubMed: 9547085]
34. Lord SR, Murray SM, Chapman K, Munro B, Tiedemann A. Sit-to-stand performance depends on sensation, speed, balance, and psychological status in addition to strength in older people. J Gerontol A Biol Sci Med Sci. 2002; 57(8):M539–543. [PubMed: 12145369]
35. Guralnik JM, Ferrucci L, Simonsick EM, Salive ME, Wallace RB. Lower-extremity function in persons over the age of 70 years as a predictor of subsequent disability.[see comment]. N Engl J Med. 1995; 332(9):556–561. [PubMed: 7838189]
36. Lezak, MD., Howieson, DB., Loring, DW. Neuropsychological Assessment Fourth edn. Oxford University Press; New York: 2004.

Figure 1.

Experimental setup with a person standing on force platform with feet 16 cm apart, viewing computer monitor 1.5 m away. Subject was instructed to keep ‘X’ inside of circle by shifting weight while keeping feet in place.

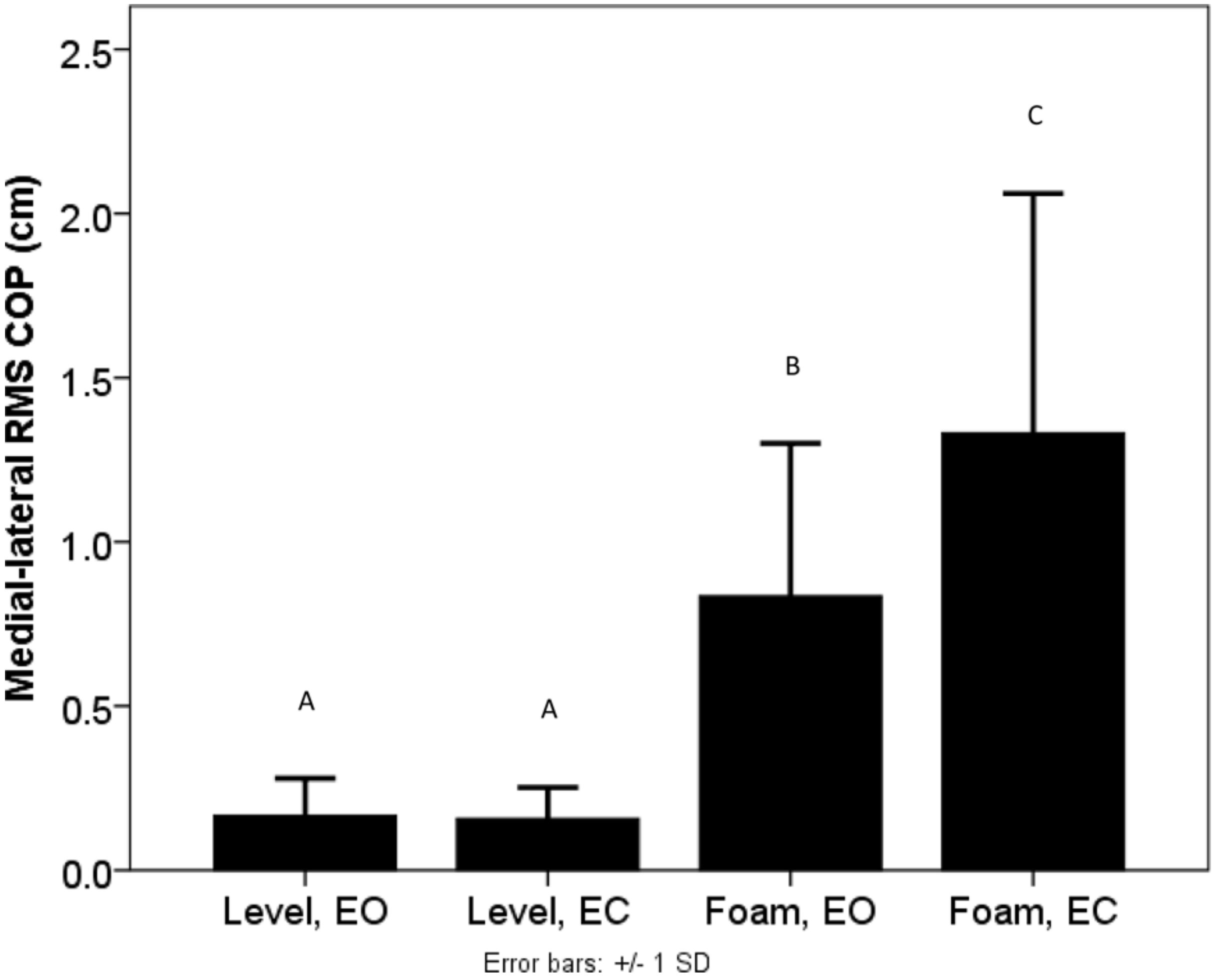

Figure 2.

Effect of sensory conditions on mean root-mean-square (RMS) of medio-lateral center of pressure (COP) displacement. Sensory conditions are Level and Foam Surface, with Eyes Open (EO) and Eyes Closed (EC). The number of subjects who completed all conditions was 123. A: Level surface conditions were not significantly different from each other ($p = 0.9$). B: Foam, Eyes Open was significantly greater than level surface conditions ($p < 0.001$). C: Foam, Eyes Closed was significantly greater than all other conditions ($p < 0.001$).

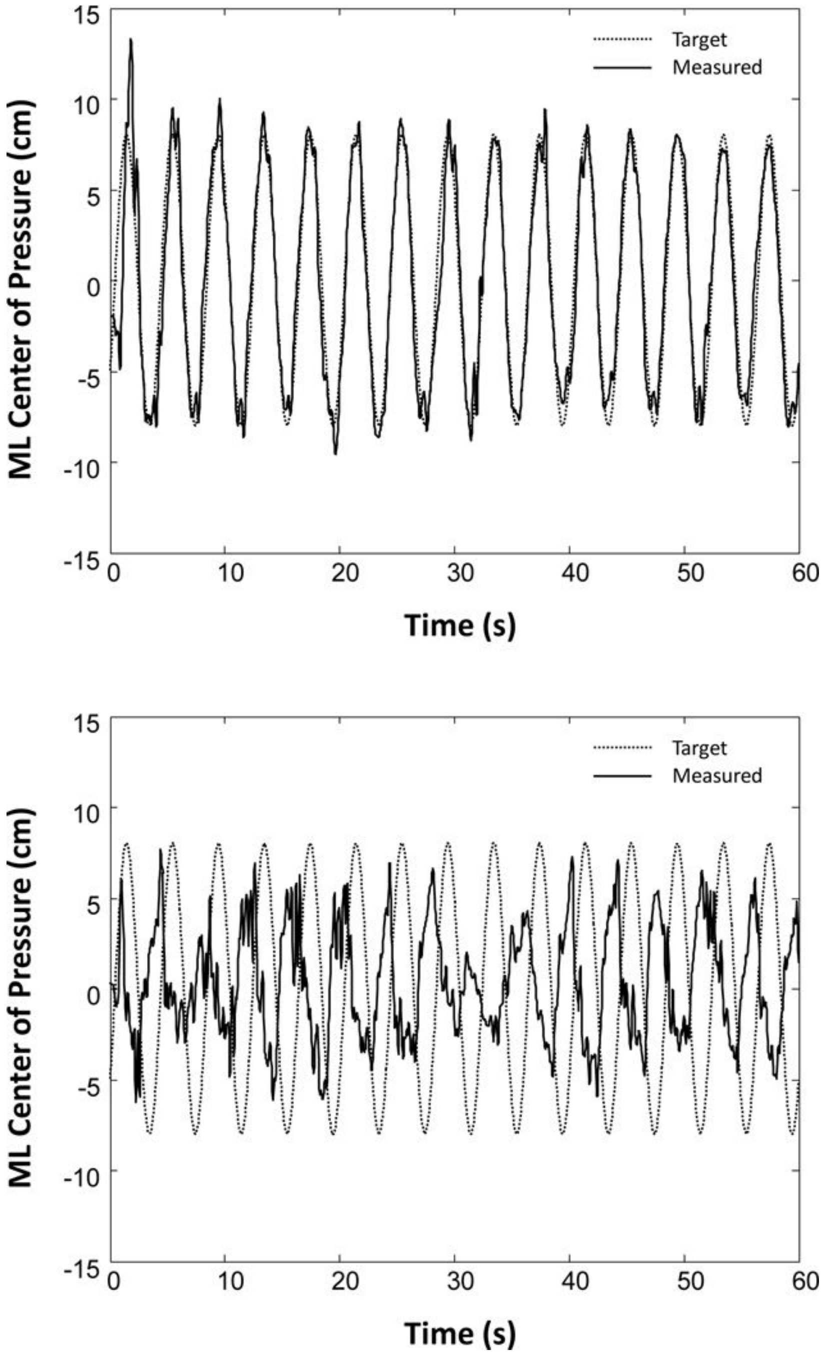

Figure 3.

Examples of medio-lateral (ML) center of pressure tracking performance in a subject with good performance (top) and poor performance (bottom). Target movement frequency was 0.25 Hz (dotted line), and subject's measured COP (solid line).

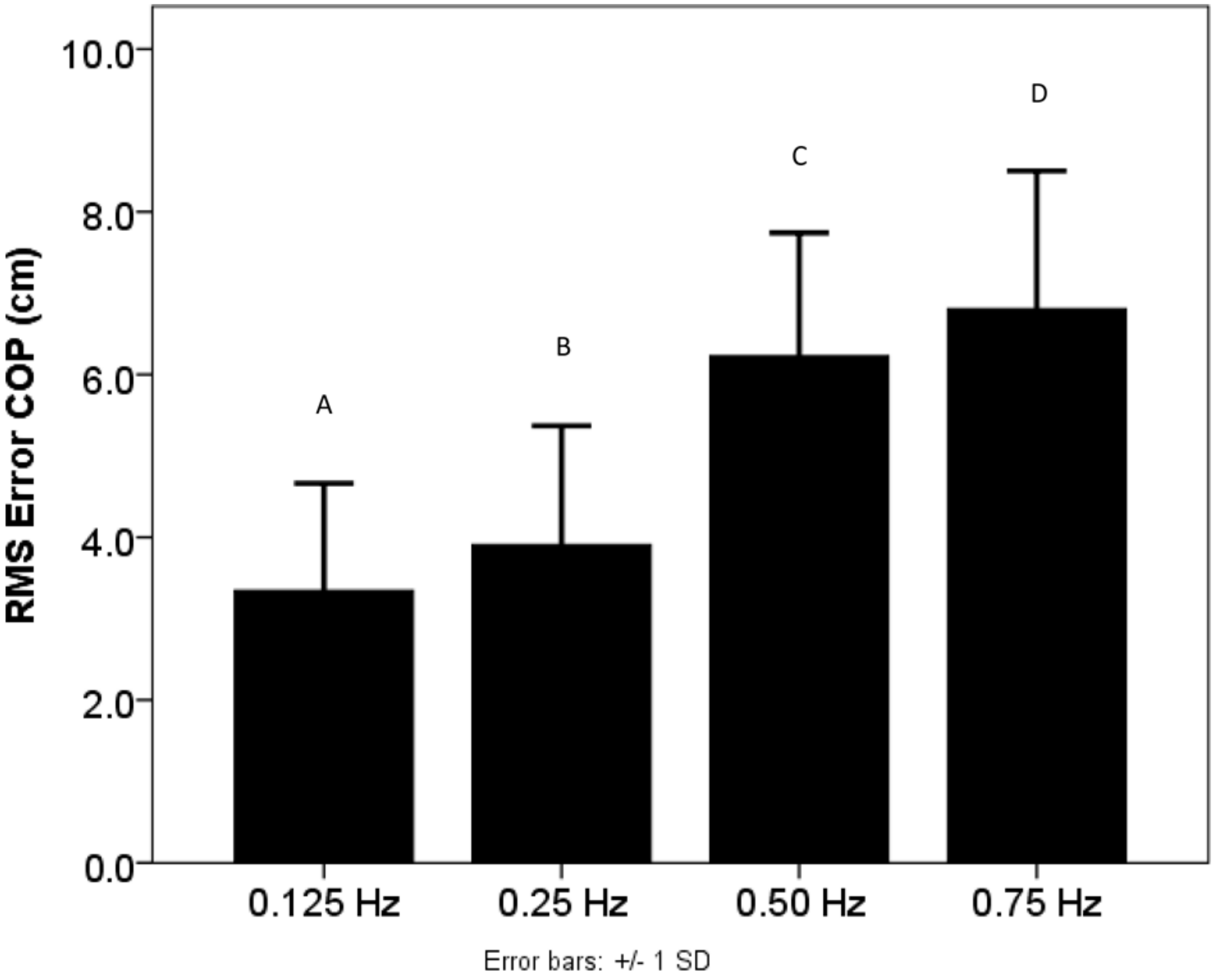

Figure 4.

Effect of target frequency on mean root-mean-square (RMS) error between target location and center of pressure (COP) location in medial-lateral direction. The number of subjects who completed all conditions was 192. A, B, C, D: Each target frequency condition was significantly different from all other conditions ($p < 0.001$).

Table 1

Subject demographics and performance on executive function and physical function tests. Means and standard deviation (SD) are displayed for normally distributed variables. Median and interquartile range (IQR) are shown for non-normally distributed data

Variable	**Mean (SD)**
Age (y)	85 (3)
Body Mass Index (kg/m^2)	27.3 (4.4)
Gender	55% female
Six meter Gait Speed (m/s)	0.99 (0.20)
Modified Mini-Mental State	93 (7)
Contributors of balance	
Digit Symbol Substitution Task (# correct in 90 s)	39 (13)
EXIT 15 (0 out of 30 is the best score)	Median 4, IQR 2 – 7
CLOX 1 (15 out of 15 is the best score)	Median 9, IQR 7 – 11
Peak Knee Extension Strength (Nm)	80 (26)
Abnormal sensation	54%
Timed Chair Stands (Time in s to complete 5)	14.9 (5.1)
Short Physical Performance Battery (12 is the best score)	Median 10, IQR 9 – 11

Table 2

Multiple linear regression of root mean square (RMS) medio-lateral postural sway during quiet stance on foam with eyes open (EO). Model 1 entered Age, Body Mass Index (BMI) and Sex in step 1, followed by stepwise entrance of Timed Chair Stands time. Models 2 and 3 were stratified by Sex. In Model 3, the peak knee extensor torque was also selected. β is the standardized coefficient.

Model 1: ML RMS, Foam EO	**β**	**t-statistic**	**p (t)**	**Change in R^2**	**p (Change in R^2)**
Age	0.087	1.15	0.25	0.19	< 0.001
BMI	0.197	2.61	0.01		
Sex	−0.392	−5.15	< 0.001		
Timed Chair Stands	0.306	4.02	<0.001	0.09	< 0.001
Model 2: ML RMS, Foam EO stratified by male sex					
Age	0.266	2.26	0.027	0.10	0.048
BMI	0.117	0.99	0.33		
Timed Chair Stands	0.316	2.69	0.009	0.10	0.009
Model 3: ML RMS, Foam EO stratified by female sex					
Age	0.012	0.11	0.91	0.077	0.069
BMI	0.088	0.76	0.45		
Timed Chair Stands	0.383	3.66	0.001	0.12	0.002
Peak Knee Extensor Torque	0.373	3.19	0.002	0.11	0.002

Table 3

Multiple linear regression of root mean square (RMS) error between medio-lateral postural sway tracking and 0.25 Hz target movement. Model 1 entered Age, Body Mass Index (BMI) and Sex in step 1, followed by stepwise entrance of Digit Symbol Substitution Test score. Models 2 and 3 were stratified by Sex. β is the standardized coefficient.

Model 1: ML RMS Error, 0.25 Hz	**β**	**t-statistic**	**p (t)**	**Change in R^2**	**p (Change in R^2)**
Age	0.080	1.20	0.23	0.16	< 0.001
BMI	0.011	0.17	0.86		
Sex	0.395	6.06	< 0.001		
Digit Symbol Substitution Test	−0.213	−3.18	0.002	0.04	0.002
Model 2: ML RMS Error, 0.25 Hz stratified by male sex					
Age	0.001	0.01	0.99	0.005	0.80
BMI	0.028	0.26	0.79		
Digit Symbol Substitution Test	−0.177	−1.59	0.12	0.029	0.12
Model 3: ML RMS Error, 0.25 Hz stratified by female sex					
Age	0.154	1.63	0.11	0.041	0.11
BMI	0.001	0.01	0.99		
Digit Symbol Substitution Test	−0.277	−2.92	0.004	0.073	0.004