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Failure on the foam eyes closed test of standing balance associated with reduced semicircular canal function in healthy older adults

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Abstract

Purpose—Standing on foam with eyes closed (FOEC) has been characterized as a measure of vestibular function; however, the relative contribution of vestibular function and proprioceptive function to the FOEC test has not been well described. In this study we investigate the relationship between peripheral sensory systems (vestibular and proprioception) and performance on the FOEC test in a cohort of healthy adults.

Subjects—563 community dwelling healthy adults (mean age 72.7 (SD = 12.6) years, range 27–93 years) participating in the Baltimore Longitudinal Study of Aging were tested.

Methods—Proprioceptive threshold (PROP) was evaluated with passive motion detection at the right ankle. Vestibulo-ocular reflex (VOR) gain was measured using video head impulses. Otolith function was measured with cervical and ocular vestibular evoked myogenic potentials (oVEMP and cVEMP). Participants stood on FOEC for 40 seconds while wearing BalanSens (BioSensics, LLC) to quantify center of mass sway area (COM). A mixed model multiple logistic regression was used to examine the odds of passing the FOEC test based on PROP, VOR, cVEMP and oVEMP function in a multi-sensory model while controlling for age and gender.

Results—The odds of passing the FOEC test decreased by 15% ($p < 0.001$) for each year of increasing age and by 8% with every 0.1 reduction in VOR gain ($p = 0.025$). Neither PROP nor otolith function was significantly associated with passing the FOEC test.

Conclusions—Failure to maintain balance during FOEC may serve as a proxy for rotational vestibular contributions to postural control. Semicircular canals are more sensitive to low frequency motion than otoliths which may explain these relationships since standing sway is dominated by lower frequencies. Lower VOR gain and increased age independently decreased the odds of passing the test.

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Keywords

Vestibular; Postural Sway; Foam; Eyes Closed

Introduction

Standing on foam with eyes closed (FOEC) is an example of a clinical balance test thought to identify balance impairments that are consistent with vestibular impairments (Agrawal et al. 2009; Koo et al. 2015; Shumway-Cook & Horak 1986). This particular balance test is based on the original Romberg test (Romberg 1853) and was also included as a component of the Clinical Test of Sensory Interaction on Balance (Shumway-Cook & Horak 1986). Some individuals with vestibular loss lose their balance when attempting this test (Cohen et al. 1993; Alhanti et al. 1997; Cohen et al. 2014a). However, not all investigations of the FOEC test have demonstrated a relationship with vestibular function in older adults (Lord et al. 1991; Jacobson et al. 2011).

Older adults tend to have reduced vestibular and proprioceptive function (Li et al. 2015b; Deshpande et al. 2016; Li et al. 2015a; Paige 1992), which may impact balance via more sway without a complete loss of balance when standing on foam (Illing et al. 2010; Choy et al. 2003; Cohen et al. 1993; Anson et al. 2017). Increased sway when standing on a foam cushion with eyes closed may be due to reduced vestibular function or reduced proprioception (Isableu & Vuillerme 2006; Anson et al. 2017). The ability to stand on FOEC depends on intact sensory reweighting ability to prevent loss of balance since head motion in space may be incongruent with ankle motion because of the foam cushion (Choy et al. 2003; Cohen et al. 1993; Alhanti et al. 1997). Age related proprioceptive or vestibular impairment could reduce sensory redundancy and make sensory reweighting more difficult via reduced or less accurate sensory signals (Horak & Hlavacka 2001; Horak et al. 1990; Ko et al. 2015; Deshpande et al. 2016). However, it is unclear whether isolated tests of vestibular and proprioceptive function are related to maintaining standing on FOEC in healthy aging.

During standing both the semicircular canals and otolith organs will sense head motion. Therefore, clinical diagnostic tests of vestibular function [head impulse test (Halmagyi & Curthoys 1988), and ocular/cervical vestibular evoked myogenic potential (oVEMP/cVEMP) (Halmagyi & Curthoys 1999)] capable of separately testing aspects of angular and linear vestibular function would be needed to determine their contribution to balance. Proprioception is the sense of the position of one body segment relative to another which contributes to balance through both stereotyped reflexes and modifiable responses (Sherrington 1906; Horak et al. 1990). Since the majority of unperturbed standing sway occurs at the ankle joint, a measure of the ability to detect ankle motion would be important to quantify posturally relevant proprioceptive ability (Ko et al. 2015).

Here we investigated whether the odds of successfully completing the FOEC balance task were influenced by results from tests of vestibular and proprioceptive function. These test results were obtained in isolation and combined using a multi-sensory model also controlling for age and gender.

Methods

The Baltimore Longitudinal Study of Aging (BLSA) is an ongoing prospective cohort study initiated by the National Institute on Aging (NIA) in 1958. Participants are community-dwelling adults age 20–103 who undergo a standardized array of tests over 3 days every 1–4 years at the NIA. This study includes a cross-sectional sample of all BLSA participants seen between August 2014 and June 2016. During this time period 563 participants underwent balance testing, and of those 518 participants completed cVEMP/oVEMP testing, 483 participants were tested with the head impulse test, and 519 participants participated in proprioception testing. 404 individuals participated in all of the sensory and balance tests and were included in the analysis. Vestibular testing was performed by EA or RTB and overseen by YA. SS oversaw the proprioception testing protocol which was developed by ND. Height, weight, smoking history, and fall history in the past 12 months was also recorded. Height and weight were used to calculate BMI. All participants provided written informed consent, and the BLSA study protocol was approved by the Institutional Review Board associated with the BLSA at Harbor Hospital.

Balance Testing

Participants stood on a foam cushion (Sunmate, Dynamic Systems, Inc.) of density 72.2 kg/m^3 with their feet together, eyes closed, and hands on their hips and were provided with up to three attempts to complete one trial lasting 40 seconds (Wu et al. 2009). Successful completion of a trial was noted as ‘pass’ (n = 487) and loss of balance prior to completion of the trial was noted as ‘fail’ (n = 76). Loss of balance was defined as opening eyes, taking a step, changing hand position, touching the wall, or needing assistance to prevent a fall regardless of when in the trial it occurred. Participants were excluded from the balance testing if they required assistance to stand from sitting or to walk.

Vestibular Function Tests

Individuals participating in the BLSA underwent tests for both semicircular canal function (head impulse test) and otolith function (cervical VEMP and ocular VEMP) as described below.

Video Head Impulse Testing—Methods to measure lateral semicircular canal function have been published previously (Halmagyi & Curthoys 1988) and validated in older adults (Agrawal et al. 2014; Schneider et al. 2009; MacDougall et al. 2009; Bartl et al. 2009). In brief, participants wore the EyeSeeCam video-oculography system, a lightweight goggle frame with a built in accelerometer to record head movement and camera to record eye movements at a sampling frequency of 220 Hz (Interacoustics USA, Eden Prairie, MN). Participants sat approximately 1.25 meters from a wall with a visual fixation target. Trained examiners tilted the participant’s head 30 degrees below horizontal to bring the horizontal semicircular canal into the plane of head rotation and then performed 10–15 small amplitude (15–20°) head impulses to the right and left, with peak velocity typically from 150 to 250 degrees per second. Horizontal VOR gain was calculated as the ratio of the eye velocity and head velocity 60ms after the onset of the head impulse (Agrawal et al. 2014). Participants were excluded from the head impulse testing if they had restricted neck rotation or pain with neck rotation.

Vestibular evoked myogenic potential (VEMP) recording conditions

A commercial electromyographic (EMG) system (Carefusion Synergy, software version 14.1, Dublin, OH, USA) was used to record EMG signals with disposable, self-adhesive, pregelled, Ag/AgCl electrodes with 40-inch safety lead wires from GN Otometrics (Schaumburg, IL, USA). EMG signals were amplified 2500x and band-pass filtered, 20–2000 Hz for cervical VEMPs (Nguyen et al. 2010).

Ocular VEMPs—Subjects reclined with their upper bodies elevated at 30 degrees from horizontal. The skin overlying both cheeks and the manubrium sterni was cleansed with alcohol preps before electrode placement. A noninverting electrode was placed on the cheek approximately 3 mm below the eye, directly beneath the pupil, the inverting electrode was placed 2 cm below the noninverting electrode and a ground electrode was placed on the manubrium sterni. Before stimulation, participants performed 20-degree vertical saccades to ensure that symmetrical signals were recorded from both eyes. Participants were instructed to maintain a 20° upward gaze during midline tap stimuli, 50 head taps delivered manually with a reflex hammer (Aesculap model ACO12C) fitted with an inertial microswitch trigger. Head taps were delivered at Fz, in the midline at the hairline, 30% of the distance between the inion and nasion. Fifty head taps were averaged for each test. The oVEMP waveform consists of a negative peak (n10), identified as the first distinctive peak in the waveform, followed by a positive peak (p16), identified as the first distinctive trough in the waveform. Individuals with EMG recordings lacking definable n10 waves were defined as having an absent oVEMP response. oVEMP function was dichotomized as present (response in one or both ears) or bilaterally absent. Participants were excluded from the oVEMP test if they could not see the target or if they had a positive Rinne screening.

Cervical VEMPs—Participants reclined such that their upper bodies were elevated 30 degrees from horizontal. A noninverting electrode was placed at the midpoint of the sternocleidomastoid (SCM) muscle, an inverting electrode was placed on the sternoclavicular junction, and a ground electrode was placed on the manubrium sterni. Participants were instructed to lift their heads up and hold turned to the side to provide tonic background SCM activity during stimulation, and a pre-stimulus rectified surface EMG signal of at least 50 μV over 10 ms was required for accepting a cervical VEMP (cVEMP) tracing. Air-conducted sound stimuli consisted of 500 Hz, 125 dB SPL tone bursts of positive polarity, with a linear envelope (1 ms rise/fall time, 2 ms plateau), at a repetition rate of 5 Hz. Sound stimuli were delivered monaurally through Audiocups noise-excluding headset enclosures (Amplivox, Eden Prairie, MN). The cVEMP waveform consists of a positive peak (p13), identified as the first distinctive trough in the waveform, followed by a negative peak (n23), identified as the first distinctive peak in the waveform. Subjects with EMG recordings lacking definable p13 waves were defined as having an absent cVEMP response. cVEMP function was dichotomized as present (in one or both ears) or bilaterally absent. Participants were excluded from the cVEMP test if they had pain with turning their head fully to the side or if they had a positive Rinne screening.

Proprioception Testing—Proprioception threshold (PROP) at the ankle has been detailed previously and is described here in brief (Ko et al. 2015). Participants sat blindfolded on a chair with their right foot on a motorized pedal connected to a potentiometer measuring angular position of the ankle joint. The threshold test identified the minimal angular displacement (degrees) required for correct perception of passive movement direction (plantar flexion or dorsiflexion) at an angular speed of 0.3°/s. Participants push a button to indicate perception of ankle motion and verbally indicate the direction of rotation. The testing followed the pre-set sequence of ankle plantar flexion, dorsiflexion, dorsiflexion, and plantar flexion. The average of the angular displacement for the last two tests was used as the proprioception threshold (Ko et al. 2015). Higher values on threshold testing correspond to less sensitive ankle proprioception.

Data Analysis

A mixed model multiple logistic regression was used to determine whether the odds of passing the FOEC balance test depended on PROP, VOR gain, cVEMP and oVEMP function while controlling for age and gender. STATA 14 (College Station, TX, USA) was used for all analyses. The logistic regression analysis was considered statistically significant at $\alpha = 0.05$.

Results

Participant demographics are presented in Table 1. 487 of 563 participants (86.5%) performed the FOEC test without a loss of balance. The mean age of participants who successfully completed the FOEC test (n = 487) was 71.4 [(SD = 12.7), range 27–93] and 54.6% of the participants were female. The mean age of participants who did not complete the FOEC test (n = 76) was 82.9 [(SD = 6.4), range 32–93] and 47.4% of the participants were female.

FOEC Failure vs. Success

Individuals were 15% more likely to fall on FOEC with every 1 year increase in age (OR = 0.85, $p < 0.0010$). The odds of falling on FOEC increased by 8% with every 0.10 decrease in VOR gain (OR = 9.25, $p = 0.022$). PROP, oVEMP and cVEMP function did not significantly contribute to the odds of passing the FOEC balance task without losing balance, see Table 2. Including history of falling in the model did not meaningfully change the results (data not shown). Categorizing VEMP responses as present, unilaterally absent, and bilaterally absent did not meaningfully change the results (data not shown). Therefore, VEMP categories were collapsed to simplify the data reporting.

Discussion

Impaired horizontal semicircular canal function was associated with an increased odds of failing the FOEC balance test. Otolith function and ankle proprioception were not associated with the ability to pass the FOEC test. The response frequencies of the otoliths and semi-circular canals are different; therefore they may contribute to different aspects of postural control (Carriot et al. 2015). The majority of standing sway power is in the lower frequency range, and for neurons that receive both rotation and linear head motion signals the angular component dominates at lower frequencies (Carriot et al. 2015). Although the video head impulse VOR gain measure of semicircular canal function is high frequency, we believe that more generally the current results suggest that VOR gain serves as a proxy measure for the angular vestibular contributions to standing balance. During standing the angular acceleration of the head at the top of the inverted pendulum may be a more meaningful input signal for balance than signals representing deviation from vertical from the otoliths.

The association between rotational vestibular function and successful balance was independent of the effect of age. Thus, it is likely that progressive vestibular loss such as occurs with age initially results in increased sway which progresses to an inability to maintain balance on FOEC (Serrador et al. 2009). Closed loop postural control includes many facets that change with age in addition to sensory function, including multisensory integration (Mahoney et al. 2015), muscle force production and flexibility (Palmer & Thompson 2016), and mental state (anxiety or fear) (Naranjo et al. 2015) any of which can also influence postural control. Otolith function as measured by VEMPs declines with age (Su et al. 2004; Li et al. 2015a) which may contribute to the increased odds of failing the FOEC test with increasing age, despite the lack of significant relationships with VEMP results in the multivariate model. Additionally, age related delays in the postural control loop between the sensory input and motor response may result in additional challenges for older adults not captured in this analysis (Wiesmeier et al. 2015). Age was not significantly associated with sway area in the FOEC condition in which we reported on a subset of this cohort that did not include any individuals who failed the balance task (Anson et al. 2017). In multivariate analyses age related sensory ability accounted for the bivariate relationships between age and sway area for the FOEC balance task.

The individuals who failed the FOEC balance test were more likely to be older than those who passed the FOEC balance test. Others have reported that older adults stood for shorter time with eyes closed on foam compared to younger adults (Cohen et al. 1993; Anacker & Di Fabio 1992). It is possible that the individuals who were unable to maintain balance on FOEC also exhibited decline in other areas. We included age in the regression model in order to account for these factors. Future studies should focus on identifying whether additional phenotypic differences exist among individuals who are unable to complete this balance task.

Since the purpose of standing on foam is to make proprioception less reliable for postural control, it may not come as a surprise that proprioception was not significantly associated with COM sway while standing on foam with eyes closed. This is in contrast to results demonstrating an association between proprioception and balance ability while standing on a firm surface (Deshpande et al. 2016). Standing balance on a firm surface is also impaired when touch/pressure receptor function is degraded in MS (Citaker et al. 2011). It is not clear whether this would negatively impact balance on a foam surface and touch thresholds were not captured in this cohort. It should be noted that all of the sensory tests used in this study were performed separately from the balance test and the current results do not reflect dynamic reweighting. Additionally, participants were supine for VEMP testing and seated for PROP and head impulse testing. Vestibular reflexes have been shown to increase under postural challenge (Naranjo et al. 2015), sensitivity to proprioception may also be elevated when standing compared to sitting. While isolated tests are important for diagnosis of disease specific pathology, future studies are needed to determine how testing context influences the use of specific sensory information for postural control.

Limitations

Although these results suggest that only semicircular canal function may lead to loss of balance, testing the sensory function while not performing a balance task may result in reduced sensitivity to identify true relationships. These data are cross-sectional and cannot be used to support causal inferences between the ability to pass the FOEC test and age, vestibular, or proprioceptive function. We only considered horizontal VOR gain as a proxy for semicircular canal function in this study and future studies will need to establish whether these relationships differ for the vertical semicircular canals which may contribute differently to postural control. We modeled VEMP responses as present or absent rather than as continuous amplitudes to allow for inclusion of participants that would have been excluded due to absent VEMP responses. We did examine the reduced data set based on continuous VEMP amplitudes and there was no difference in the relationship between VEMPs and the odds of passing the FOEC test (data not shown). The measure of proprioception used in this study is behavioral and the results may differ if a more physiologic measure of proprioception like somatosensory evoked potentials was used. The video head impulse test was insensitive to caloric asymmetries in the mild to moderate range (McCaslin et al. 2014; Cohen et al. 2014b). The results may differ if a caloric measure of asymmetry was used to quantify vestibular function.

Conclusion

Individuals with lower VOR gain and increased age were less likely to pass the foam eyes closed balance test. The results of this study provide further support that performance on the FOEC balance test is influenced by the function of the vestibular system even without complete loss of vestibular function.

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References

Agrawal Y, Carey JP, Della Santina CC, et al. 2009; Disorders of balance and vestibular function in US adults: data from the National Health and Nutrition Examination Survey, 2001–2004. Arch Intern Med. 169:938–44. [PubMed: 19468085]

Agrawal Y, Schubert MC, Migliaccio Aa, et al. 2014; Evaluation of Quantitative Head Impulse Testing Using Search Coils Versus Video-oculography in Older Individuals. Otol Neurotol. 35:283–288. [PubMed: 24080977]

Alhanti B, Bruder LA, Creese W, et al. 1997; Balance Abilities of Community Dwelling Older Adults Under Altered Visual and Support Surface Conditions. Phys Occup Ther Geriatr. 15:37–52.

Anacker SL, Di Fabio RP. 1992; Influence of sensory inputs on standing balance in community-dwelling elders with a recent history of falling. Phys Ther. 72:575–584. [PubMed: 1635942]

Anson E, Bigelow RT, Swenor B, et al. 2017; Loss of Peripheral Sensory Function Explains Much of the Increase in Postural Sway in Healthy Older Adults. Front Aging Neurosci. 9:202. [PubMed: 28676758]

Bartl K, Lehnen N, Kohlbecher S, et al. 2009; Head Impulse Testing Using Video-oculography. Ann N Y Acad Sci. 1164:331–333. [PubMed: 19645921]

Carriot J, Jamali M, Brooks JX, et al. 2015; Integration of canal and otolith inputs by central vestibular neurons is subadditive for both active and passive self-motion: implication for perception. J Neurosci. 35:3555–65. [PubMed: 25716854]

Choy NL, Brauer S, Nitz J. 2003; Changes in Postural Stability in Women Aged 20 to 80 Years. Journals Gerontol Ser A Biol Sci Med Sci. 58:M525–M530.

Citaker S, Gunduz AG, Guclu MB, et al. 2011; Relationship between foot sensation and standing balance in patients with multiple sclerosis. Gait Posture. 34:275–278. [PubMed: 21683600]

Cohen H, Blatchly CA, Gombash LL. 1993; A study of the clinical test of sensory interaction and balance. Phys Ther. 73:346–51. [PubMed: 8497509]

Cohen HS, Mulavara AP, Peters BT, et al. 2014a; Standing balance tests for screening people with vestibular impairments. Laryngoscope. 124:545–550. [PubMed: 23877965]

Cohen HS, Sangi-Haghpeykar H, Ricci NA, et al. 2014b; Utility of stepping, walking, and head impulses for screening patients for vestibular impairments. Otolaryngol Neck Surg. 151:131–136.

Deshpande N, Simonsick E, Metter EJ, et al. 2016; Ankle proprioceptive acuity is associated with objective as well as self-report measures of balance, mobility, and physical function. Age (Dordr). 38:53. [PubMed: 27146830]

Halmagyi GM, Curthoys IS. 1988; A clinical sign of canal paresis. Arch Neurol. 45:737–739. [PubMed: 3390028]

Halmagyi GM, Curthoys IS. 1999; Clinical testing of otolith function. Ann N Y Acad Sci. 871:195–204. [PubMed: 10372072]

Horak FB, Hlavacka F. 2001; Somatosensory loss increases vestibulospinal sensitivity. J Neurophysiol. 86:575–85. [PubMed: 11495933]

Horak FB, Nashner LM, Diener HC. 1990; Postural strategies associated with somatosensory and vestibular loss. Exp Brain Res. 82:167–77. [PubMed: 2257901]

Illing S, Choy NL, Nitz J, et al. 2010; Sensory system function and postural stability in men aged 30–80 years. Aging Male. 13:202–10. [PubMed: 20201641]

Isableu B, Vuillerme N. 2006; Differential integration of kinaesthetic signals to postural control. Exp Brain Res. 174:763–8. [PubMed: 17016738]

Jacobson GP, McCaslin DL, Piker EG, et al. 2011; Insensitivity of the Romberg test of standing balance on firm and compliant support surfaces to the results of caloric and VEMP tests. Ear Hear. 32:e1–5. [PubMed: 21775891]

Ko SU, Simonsick E, Deshpande N, et al. 2015; Sex-specific age associations of ankle proprioception test performance in older adults: results from the Baltimore Longitudinal Study of Aging. Age Ageing. 44:485–90. [PubMed: 25637144]

Koo JW, Chang MY, Woo S, et al. 2015; Prevalence of vestibular dysfunction and associated factors in South Korea. BMJ Open. 5:e008224.

Li C, Layman AJ, Carey JP, et al. 2015a; Epidemiology of vestibular evoked myogenic potentials: data from the Baltimore Longitudinal Study of Aging. Clin Neurophysiol. 126:2207–2215. [PubMed: 25703943]

Li C, Layman AJ, Geary R, et al. 2015b; Epidemiology of vestibulo-ocular reflex function: data from the Baltimore Longitudinal Study of Aging. Otol Neurotol. 36:267–272. [PubMed: 25275869]

Lord SR, Clark RD, Webster IW. 1991; Postural Stability and Associated Physiological Factors in a Population of Aged Persons. J Gerontol. 46:M69–M76. [PubMed: 2030269]

MacDougall HG, Weber KP, McGarvie LA. 2009; The video head impulse test Diagnostic accuracy in peripheral vestibulopathy. Neurology. 73:1134–1141. [PubMed: 19805730]

Mahoney JR, Dumas K, Holtzer R. 2015; Visual-Somatosensory Integration is Linked to Physical Activity Level in Older Adults. Multisens Res. 28:11–29. [PubMed: 26152050]

McCaslin DL, Jacobson GP, Bennett ML, et al. 2014; Predictive Properties of the Video Head Impulse Test. Ear Hear. 35:e185–e191. [PubMed: 24801960]

Naranjo EN, Allum JHJ, Inglis JT, et al. 2015; Increased gain of vestibulospinal potentials evoked in neck and leg muscles when standing under height-induced postural threat. Neuroscience. 293:45–54. [PubMed: 25711937]

Nguyen KD, Welgampola MS, Carey JP. 2010; Test-Retest Reliability and Age-Related Characteristics of the Ocular and Cervical Vestibular Evoked Myogenic Potential Tests. Otol Neurotol. 31:793–802. [PubMed: 20517167]

Paige GD. 1992; Senescence of human visual-vestibular interactions. 1 Vestibulo-ocular reflex and adaptive plasticity with aging. J Vestib Res. 2:133–51. [PubMed: 1342388]

Palmer TB, Thompson BJ. 2016; Influence of age on passive stiffness and size, quality, and strength characteristics. Muscle Nerve. 55:305–315. [PubMed: 27348269]

Romberg, MH. A Manual of the Nervous Disease of Man. 2. Sieveking, EH, editor. London: Syndenham Society; 1853.

Schneider E, Villgrattner T, Vockeroth J, et al. 2009; Eyeseecam: An eye movement-driven head camera for the examination of natural visual exploration. Ann N Y Acad Sci. 1164:461–467. [PubMed: 19645949]

Serrador JM, Lipsitz LA, Gopalakrishnan GS, et al. 2009; Loss of otolith function with age is associated with increased postural sway measures. Neurosci Lett. 465:10–15. [PubMed: 19716400]

Sherrington, C. The integrative action of the nervous system. New Haven: Yale University Press; 1906.

Shumway-Cook A, Horak FB. 1986; Assessing the Influence of Sensory Interaction on Balance. Phys Ther. 66:1548–1550. [PubMed: 3763708]

Su HC, Huang TW, Young YH, et al. 2004; Aging effect on vestibular evoked myogenic potential. Otol Neurotol. 25:977–80. [PubMed: 15547429]

Wiesmeier IK, Dalin D, Maurer C. 2015; Elderly Use Proprioception Rather than Visual and Vestibular Cues for Postural Motor Control. Front Aging Neurosci. 7:97. [PubMed: 26157386]

Wu J, McKay S, Angulo-Barroso R. 2009; Center of mass control and multi-segment coordination in children during quiet stance. Exp Brain Res. 196:329–339. [PubMed: 19484228]

Table 1

Participant Demographics. Average age and sensory function for the cohort.

Participant Characteristics	N or Mean (SD)
Age	73.0 (12.7), range 24–94
Gender	
Female	302
Male	261
BMI	26.9 (4.4)
History of Smoking	
Smokers	n = 179
Non-Smokers	n = 359
History of Falling	
Fallers	n = 120
Non-Fallers	n = 443
PROP (deg)	1.52 (1.6), n = 519
VOR gain	0.92 (0.16), n = 483
oVEMP	
Present	n = 479
Absent Bilaterally	n = 107
cVEMP	
Present	n = 440
Absent Bilaterally	n = 135
Sway area (cm^2)	3.30 (2.76), n = 487

Table 2

Odds ratios showing the relationship between passing the FOEC balance test and sensory function, controlling for age and gender. Only participants who completed all sensory tests are included, the sample size is indicated in the table. Significant results indicated by * for $p < 0.05$.

Predictor Variables (n = 404)	OR	p	95% CI
Age	0.85	0.000*	[0.80, 0.90]
Gender			
Female	Ref	Ref	Ref
Male	1.39	0.345	[0.70, 2.76]
PROP	0.92	0.262	[0.79, 1.06]
VOR Gain	9.25	0.022*	[1.38, 65.76]
cVEMP			
Present	Ref	Ref	Ref
Bilaterally Absent	1.54	0.241	[0.75, 3.16]
oVEMP			
Present	Ref	Ref	Ref
Bilaterally Absent	1.16	0.772	[0.43, 3.09]

cVEMP – Cervical vestibular evoked myogenic potential

oVEMP – Ocular vestibular evoked myogenic potential

OR – Odds Ratio

Ref – Reference

VOR – Vestibulo-ocular reflex