Experimental Gerontology 184 (2023) 112338

Contents lists available at ScienceDirect

Experimental Gerontology

journal homepage: www.elsevier.com/locate/expgero

Effects of free versus restricted arm movements on postural control in normal and modified sensory conditions in young and older adults

E. Johnson [a], T.J. Ellmers [b], T. Muehlbauer [c], S.R. Lord [d], M.W. Hill [a,*]

[a] *Centre for Physical Activity, Sport and Exercise Sciences, Coventry University, Coventry, United Kingdom*
[b] *Department of Brain Sciences, Imperial College London, London, United Kingdom*
[c] *Division of Movement and Training Sciences/Biomechanics of Sport, University of Duisburg-Essen, Essen, Germany*
[d] *Falls, Balance and Injury Research Centre, Neuroscience Research Australia, University of New South Wales, Sydney, New South Wales, Australia*

ARTICLE INFO

Section Editor: Christiaan Leeuwenburgh

Keywords:
Task difficulty
Arm movements
Postural sway
Postural strategy
Upper limbs
Age

ABSTRACT

The purpose of this study was to explore the effects of arm movements on postural control when standing under different sensory conditions in healthy young and older adults. Fifteen young (mean ± SD age; 21.3 ± 4.2 years) and 15 older (mean ± SD age; 73.3 ± 5.0 years) adults completed the modified Romberg test, which uses four task manipulations (i.e. eyes open and eyes closed on a firm and foam surface) to compromise the fidelity of sensory feedback mechanisms. Each participant completed the tasks under two arm movement conditions: restricted and free arm movements. Centre of pressure (COP) range and frequency were calculated to characterise postural performance and strategy, respectively. Older adults showed greater COP range with restricted compared to free arm movements during all modified sensory conditions, with these effects most prominent in the medio-lateral (ML) plane (all $p < .05$, Cohen's d = 0.69–1.61). Compared to the free arm movement condition, there was an increase in ML displacement and frequency when arm movements were restricted during only the most challenging (i.e. vestibular dominant) task in young adults (all $p < .05$, d = 0.645–0.83). Finally, main age effects for the arm restriction cost (p < .05) indicates a greater reliance on an upper body strategy in older compared to young adults, independent of sensory availability/accuracy. These findings indicate that older adults compensate for the loss of accuracy in sensory input by increasing reliance on upper body movement strategies.

1. Introduction

Traditional conceptualisations view the control of unperturbed upright stance as involving two distinct muscle synergies, often referred to as ankle and hip strategies (Blenkinsop et al., 2017; Gatev et al., 1999). It is firmly established that an ankle strategy – which moves the whole body as single-segment inverted pendulum with counteractive torques at the ankle joint – is usually sufficient to minimise body sway during upright bidepal stance (Di Giulio et al., 2009; Horak, 2006; Morasso et al., 2019). However, more challenging tasks – such as standing on a narrow or foam surface – often involve the use of a hip strategy, which moves the body as a double-segment inverted pendulum with counterphase motion at the ankle and hip (Amiridis et al., 2003; Kuo and Zajac, 1993; Morasso, 2022). Recent work has also given considerable prominence for the existence of an 'upper body strategy' complementing the ankle and hip strategies during unperturbed stance. Empirical support for an upper body strategy is drawn largely from research reporting that postural control declines when the arms are constrained compared to when they are used freely, particularly during challenging lateral balance tasks in which the hip strategy is predominant (Boström et al., 2018; da Silva Costa et al., 2022; Hill et al., 2019; Johnson et al., 2023; Muehlbauer et al., 2022a, 2022b, 2022c; Objero et al., 2019; Patel et al., 2014). These collective findings suggest that arm movements serve as an integral component of unperturbed balance performance.

We have recently reported that older, compared to young adults, place a greater reliance on arm movements to correct postural errors during quiet standing, with the arm restriction cost (i.e., the difference in performance between free and restricted arm movement conditions) effects most pronounced in the medio-lateral (ML) plane (Johnson et al., 2023). In addition to impaired postural performance (i.e., increased centre of pressure [COP] amplitude), an increase in COP frequency has also been observed with restricted arm movements (Johnson et al.,

* Corresponding author.
E-mail address: matt.hill@coventry.ac.uk (M.W. Hill).

https://doi.org/10.1016/j.exger.2023.112338
Received 7 August 2023; Received in revised form 8 November 2023; Accepted 24 November 2023

2023). This was interpreted as an adaptive response from the central nervous system to increase ankle muscle stiffness (i.e., 'tighter' postural control) in situations of greater postural instability. The observed ML instability during restricted arm movement conditions, coupled with the increase in COP frequency among older adults, was attributed to age-related decrements in motor capacity and sensory function (Johnson et al., 2023). Yet, no studies have explored how age-related loss of sensory function influences the interaction between arm movements and standing postural control when the availability of sensory information is progressively and systematically manipulated.

Several assessment protocols have been devised to isolate the relative contributions of sensory inputs to postural control. For example, the modified Romberg test uses various task manipulations (i.e., closing the eyes to exclude vision and/or standing on foam to disrupt reduce proprioceptive precision) to compromise the fidelity of one or more sensory feedback sources (Lord et al., 1991; Shumway-Cook and Horak, 1986). Given the decline in sensory function with aging (Patel et al., 2009), it is unsurprising that older adults experience greater difficulty minimising postural sway during sensory feedback perturbations (e.g., removed vision and altered proprioception) compared to young adults (Anson et al., 2017; Baudry and Duchateau, 2012; Choy et al., 2003; Peterka and Black, 1990). Within the context of multisensory control of balance, it seems logical that a compensatory upper body strategy should, therefore, be more evident when visual and proprioceptive information are removed or made less accurate. Additionally, despite previous research recommending that arm placement and movement during balance assessments should be clearly defined and described (Milosevic et al., 2011; Hébert-Losier, 2017; Hill et al., 2019; Objero et al., 2019), inconsistencies persist both in clinic and in the literature. It is therefore important to explore how arm placement affects performance in clinical balance tests.

Against this background, this experiment was designed to determine whether arm movements influence postural control when standing under different conditions of availability and/or accuracy of proprioceptive and visual information in young and older adults. Our hypotheses were that (1) the amplitude and frequency of COP displacements would be greater during restricted compared to free arm movement conditions; (2) the de-stabilising effect of restricted arm movements would be more evident in modified sensory compared to normal (unaltered) conditions, as evidenced by greater displacements of the COP and a greater arm restriction cost (ARC); (3) the de-stabilising effect of restricted arm movements under modified sensory conditions will be larger in older compared to young adults, particularly in the ML plane.

2. Methods

2.1. Participants

Previous research has reported very large magnitude effect sizes for comparable outcomes during free and restricted arm movement conditions among both young and older adults (Johnson et al., 2023). A power analysis determined that a minimum of 15 participants would be required to obtain 80 % power (large effect size, $f = 0.40$, $p = .05$) when conducting a 2 (arm movement; free vs restricted) × 4 (balance condition; eyes open firm vs eyes closed firm vs eyes open foam vs eyes closed foam) way repeated measures ANOVA. Fifteen young (18–35 years) and 15 older (> 65 years) adults were recruited (Table 1). Inclusion criteria were age 18–35 and > 65 years. We excluded individuals suffering from any problems that may interact with postural control, including (1) musculoskeletal dysfunction, (2) neurological impairment, (3) orthopaedic pathology, (4) dementia, (5) medications which could depress the nervous system, and (6) any recent injury. All participants voluntarily enrolled in this study and provided written informed consent. The experimental procedures were carried out in accordance with the standards outlined in the declaration of Helsinki (1964) and the study received approval by an institutional ethics committee.

Table 1
Mean ± SD participant characteristics.

	Young adults ($n = 15$)	Older adults ($n = 15$)	*p* value
Sex (women; *n*)	7	7	
Age (years)	21.3 ± 4.2	73.3 ± 5.0	**0.001**
Body height (m)	1.70 ± 0.09	1.66 ± 0.14	0.693
Body mass (kg)	66.7 ± 16.2	70.4 ± 16.5	0.390
BMI (kg/m^2)	22.9 ± 4.4	25.2 ± 4.4	0.234
Falls in previous year, # of participants (%)	0/15 (0 %)	6/15 (40 %)	**0.010**
FES-I (16–64)	16.6 ± 0.5	21.3 ± 4.7	**0.001**
IPAQ total activity (min•wk.$^{-1}$)	219.7 ± 94.0	146.7 ± 57.2	**0.016**
TUG (s)	5.03 ± 0.80	7.70 ± 1.53	**0.001**
TMT-B (s)	28.0 ± 6.2	48.9 ± 18.5	**0.001**

BMI; body mass index, FES—I; falls efficacy scale-international, I-PAQ; international physical activity questionnaire, TUG; timed-up-and-go test, TMT—B; trail-making test part-B. Bold values indicate statistically significant differences between age groups (p < .05).

2.2. Baseline characteristics

Prior to experimental trials, participants completed baseline assessments, which served to characterise both age groups and confirm that participants met the inclusion criteria for the study (Table 1). Participants initially completed questionnaires for physical activity (International Physical Activity Questionnaire [I-PAQ]) (Lee et al., 2011) and concern about falling (16-item Falls Efficacy Scale International [FES—I] (Yardley et al. (2005)). As a measure of functional mobility, participants completed the Timed-Up-and-Go Test (TUG), as described by Podsiadlo and Richardson (1991). This test involves participants being timed whilst they stand up from a chair, walk three metres, turn around, and return to the chair and sit back down. The Trail Making Test part-B (TMT—B) was used to evaluate executive function (Lezak et al. 2004).

2.3. Experimental procedure

During a single visit to the laboratory, participants completed the modified Romberg test in which sensory information that is available and reliable is progressively manipulated across four conditions. In first condition, participants stand on a firm surface with the eyes open (EO-FI), where all three sensory systems are uncompromised (i.e., "normal"; Fig. 1A). The second condition represents the "proprioceptive dominant" trial (Fig. 1B), where vision is removed by closing the eyes while standing on a firm surface (EC-FI). The next condition represents the "visual dominant" trial (Fig. 1C), where reliability of proprioceptive stimuli is manipulated by having the participant stand on a foam surface with the eyes open (EO-FO). The final condition represents the "vestibular dominant" trial (Fig. 1D), where participants stand on a foam surface with the eyes closed (EC-FO), removing vision and reducing the precision of proprioception. To ensure consistency between trials, participants stood with the feet together (right and left hallux and calcaneus together). We used a foam block (Balance-pad Plus, Alcan Airex AG, Switzerland; 50 cm in length and breadth, 6 cm in height and a density of 0.55 kg/m^3) for the foam task conditions. Throughout all tests, the investigator stayed close to the participants to prevent falling but without interfering with balance performance. Each task was performed under two conditions: (1) hands clasped in front of the body (i.e., restricted arm movement) and (2) arm movement without restriction (i.e., free arm movement). For the free arm movement condition, participants were instructed they could move their arms freely and to their advantage. For the restricted arm position, compliance to the instructions was monitored visually by the investigators. After one practice trial, balance performance was assessed in two blocks (free vs.

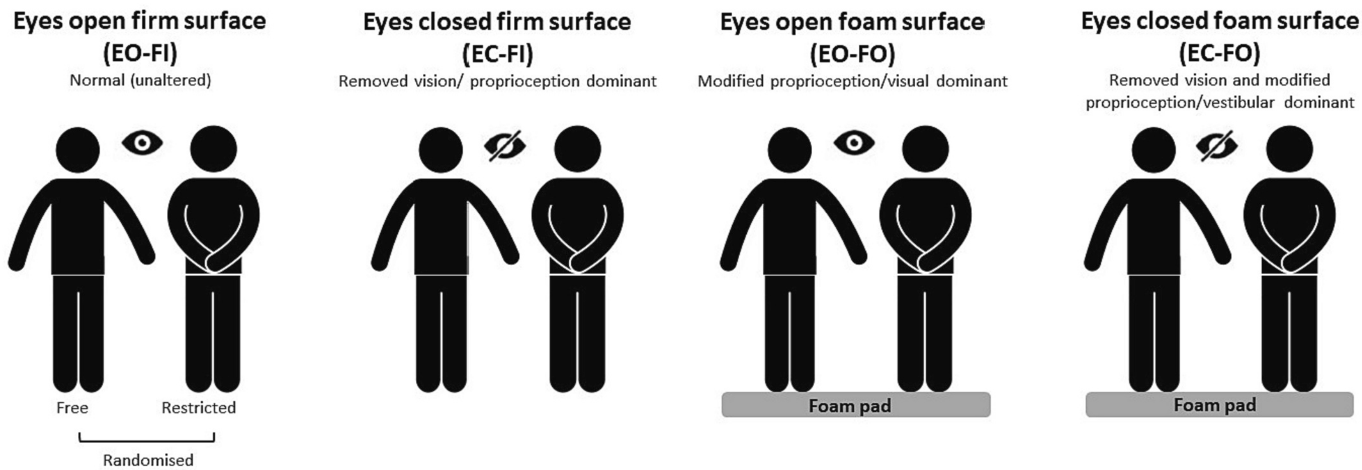

Fig. 1. Schematic of the different sensory conditions and arm positions.

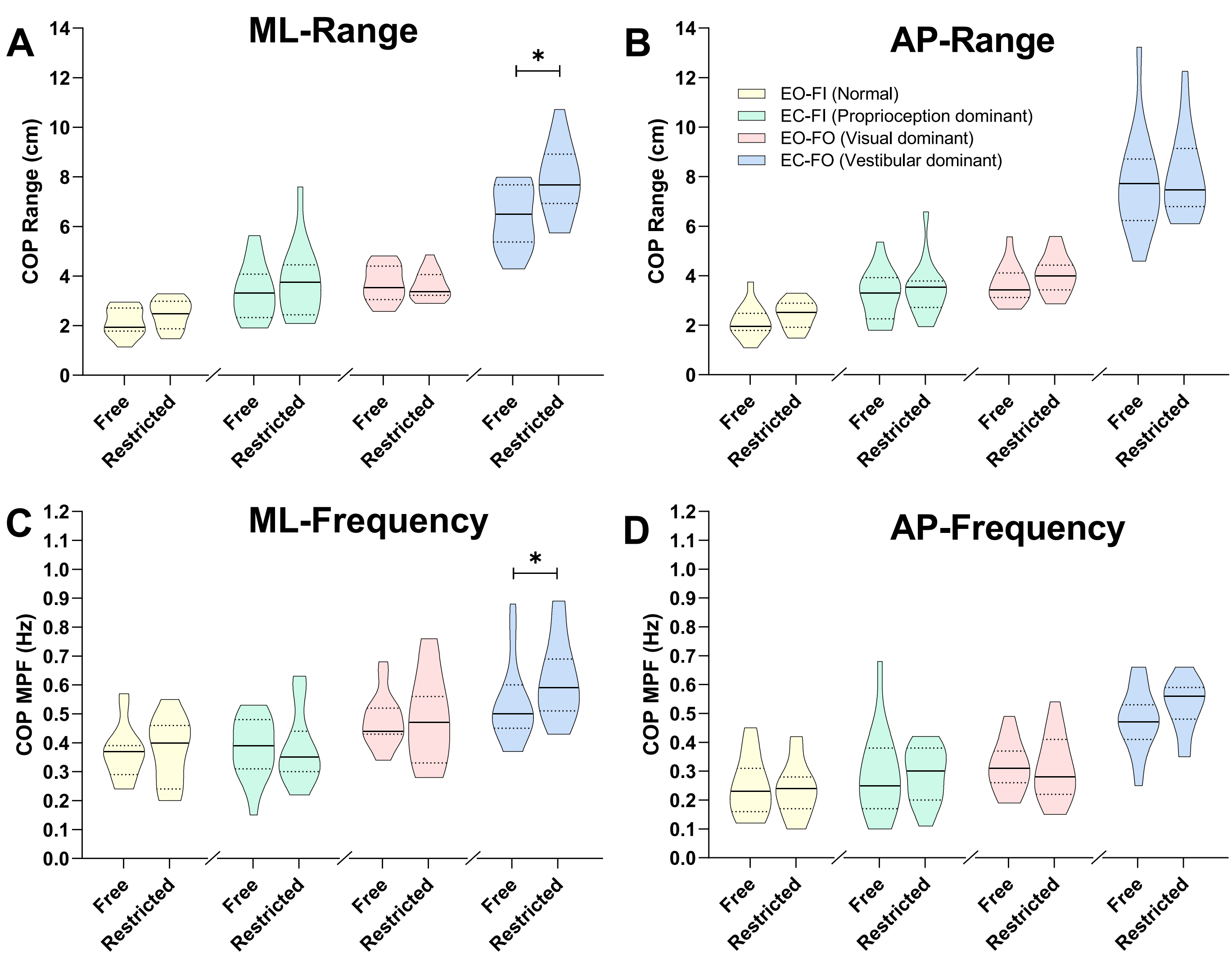

Fig. 2. Violin plots showing differences in standing balance outcomes between free and restricted arm movement conditions across the four sensory conditions in young adults. Each violin represents the median (centre line), 25th % (bottom of the violin) and 75th % (top of the violin) percentile. *Statistically significant difference between free and restricted arm movement conditions ($p < .05$). Please refer to Table 2 for mean values ± SD and Table 3 for ANOVA outputs for all assessed variables.

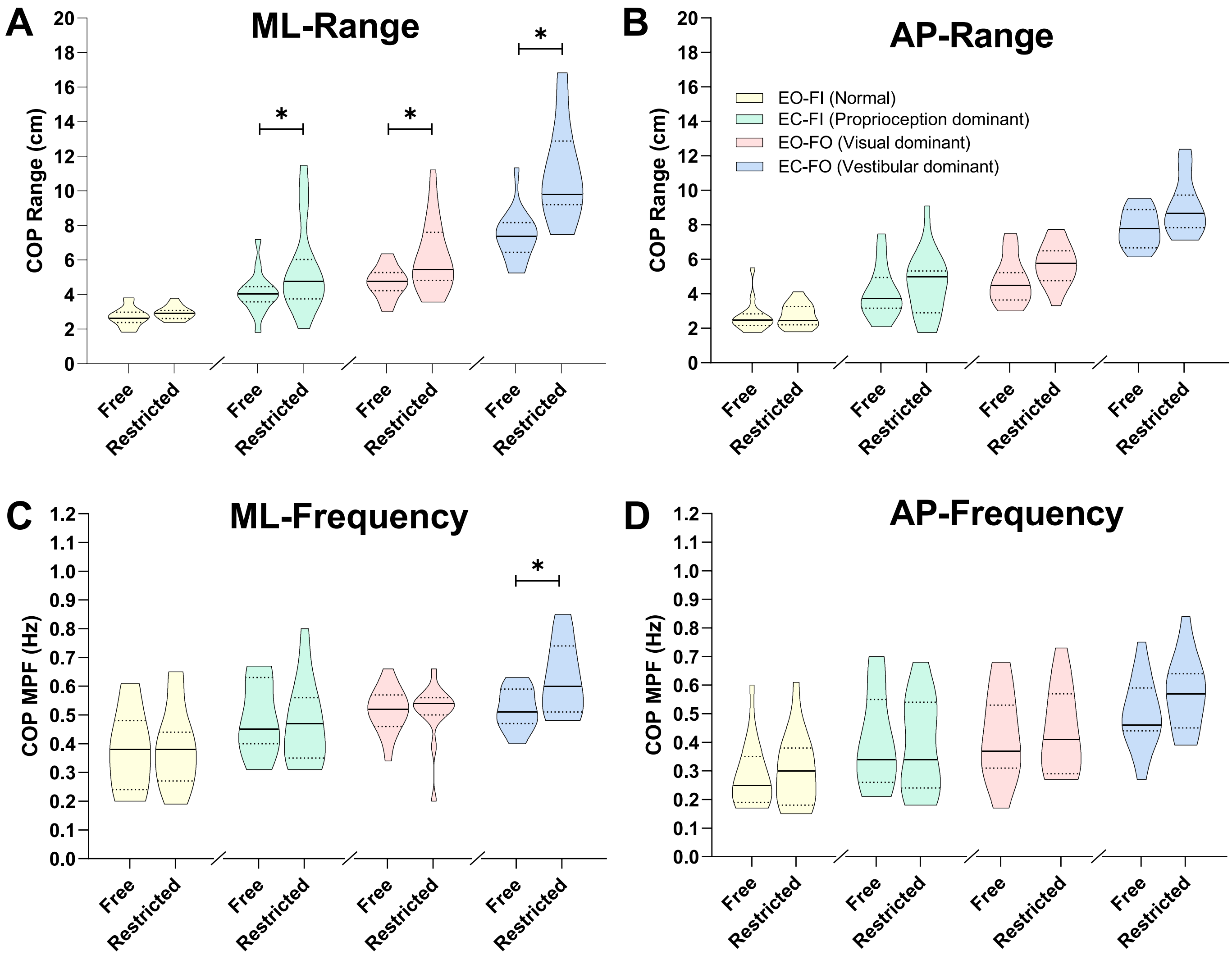

Fig. 3. Violin plots showing differences in standing balance outcomes between free and restricted arm movement conditions across the four sensory conditions in older adults. Each violin represents the median (centre line), 25th % (bottom of the violin) and 75th % (top of the violin) percentile. *Statistically significant difference between free and restricted arm movement conditions (p < .05). Please refer to Table 2 for mean values ± SD and Table 3 for ANOVA outputs for all assessed variables.

restricted), each consisting of three trials for each task. The order of the two blocks was randomised between participants. Participants completed the 'normal [EO-FI], 'proprioception dominant' [EC-FI], 'visual dominant' [EO-FO], and 'vestibular dominant' [EC-FO] conditions in that order. Participants were asked to step off the plate and rest between trials for at least 30 s. Overall, testing of one participant comprised 24 recorded 30-s data-collection trials. The average of the three trials for each task was used for further analysis. During all trials, participants were asked to stand quietly on a force platform. During eyes open trials, participants were asked to gaze at a black circle (10 cm diameter) three metre from the force platform, which was adjusted to the eye level of each individual. All participants stood barefoot.

2.4. Data analysis

Ground reaction force data were sampled at 100 Hz (Netforce, AMTI, Watertown, MA) and filtered using a fourth-order low-pass (6 Hz) Butterworth filter (BioAnalysis V2.2, AMTI, Watertown, MA) prior to calculation of centre of pressure (COP) parameters. The maximal displacement of the COP (range) in the mediolateral (ML) and anteroposterior (AP) directions (cm) were calculated to express the distance between the most distal points of the COP displacement, whereby greater values represent poorer postural stability (Prieto et al. 1996). We also calculated the mean power frequency (MPF; mean frequency in power spectrum after fast Fourier transformation) of COP data in both the ML and AP directions (Hz). MPF was derived following removal of the bias value from the signal. MPF has been viewed as a proxy index of ankle stiffness—the higher the frequency of COP displacements, the higher the stiffness around the ankle joint (Warnica et al., 2014). MPF was used to explore whether participants rely more on an ankle stiffening strategy in conditions where arm movements are restricted, and thus they are unable to rely on an 'upper body' strategy (Johnson et al., 2023). Whilst we acknowledge potential limitations of calculating MPF for 30-s samples (Carpenter et al., 2001), it was not feasible to collect data for longer sampling durations due to the challenging nature of the postural tasks used in the present study (i.e., standing on a foam surface with the eyes closed for 60 s would have been too challenging for some older adults). However, given that that we were primarily interested in changes in high frequency COP displacement associated with ankle stiffening strategies which is less affected by shorter sampling durations (Carpenter et al., 2001), we do not deem this a major limitation.

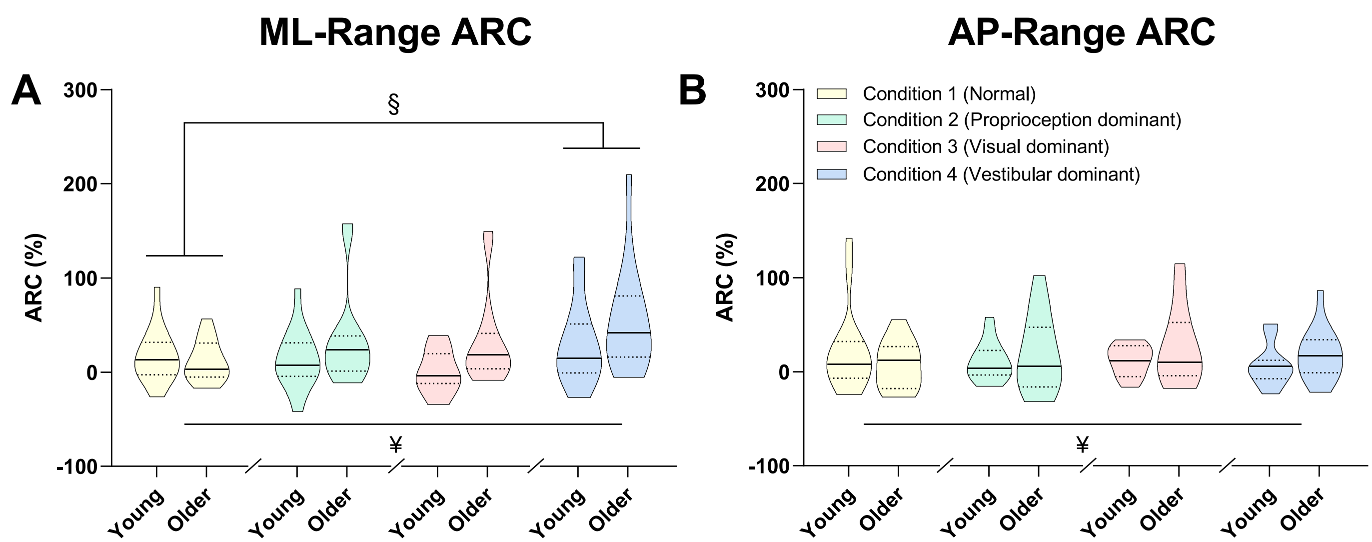

Fig. 4. Violin plots of the arm restriction cost (ARC) for age group (young vs. older adults) and sensory condition (normal, proprioception, visual and vestibular dominant) for (A) ML-Range and (B) AP-Range. Each violin represents the median (centre line), 25th % (bottom of the box) and 75th % (top of the box) percentile. § indicates a statistically significant main effect of sensory condition. ¥ indicates a statistically significant main effect of age. Please refer to Table 4 for mean values ± SD and Table 5 for ANOVA outputs for all ARC variables.

2.5. *Arm restriction cost*

To quantify the difference in performance between free and restricted arm movement conditions, we calculated the arm restriction cost (ARC) according to the previously described formula (Johnson et al., 2023): [(restricted arm condition – free arm condition) / free arm condition) * 100].[1] A positive ARC value reflects poorer postural control (i.e., increased COP amplitude) in the restricted arm condition compared with the free arm condition. Negative values on the other hand represent improved postural control (i.e., decreased COP amplitude in the restricted arm condition). The ARC has previously been shown discriminate between age and task difficulty (Johnson et al., 2023).

2.6. *Statistical analysis*

Data were analysed using SPSS version 25.0 (IBM Inc., Chicago, IL). For all analyses, assumptions of normality (Shapiro–Wilk Test) and homogeneity of variance/sphericity (Mauchly Test) were checked and met prior to conducting parametric analyses. As we have previously observed marked age-related differences in the effects of arm restriction on postural control during normal (i.e., no sensory restriction) quiet stance (Johnson et al., 2023), and due also to 'normal' Romberg performance (i.e., without the restriction of arms) showing clear age-related effects (Agrawal et al., 2011; Goble et al., 2020), we first analysed young and older adult groups separately. A series of two-way analysis of variance (ANOVA) were undertaken to test for the within-subject effects of arm (× 2 [free vs. restricted arm movement]) and sensory condition (× 4 [EO-FI vs. EC-FI vs. EO-FO vs. EC-FO) in dependent variables. We next analysed the ARC outcomes using two-way mixed model ANOVAs for the within-subject effects of sensory condition (× 4 [EO-FI vs. EC-FI vs. EO-FO vs. EC-FO) and the between subject effects of age (× 2 [young vs. older adults]). The ARC outcomes were analysed for our performance outcome (COP amplitude). Where significant interactions or main effects were detected, post-hoc analyses using Bonferroni-adjusted α determined the location of any differences. For ANOVA, effect sizes are reported as partial eta-squared value (η^2). The magnitude of differences between trials was expressed as standardised mean difference (Cohen's *d* effect sizes). Threshold values for Cohen's *d* statistics were < 0.20 = trivial; 0.20–0.59 = small; 0.60–1.1 = moderate, and > 1.20 = large. The alpha value was a priori set at $p < .05$ for all tests.

3. Results

Tables 2 and 4 presents the mean values ± SD for all balance

Table 2
Mean ± SD for all standing COP outcomes for the young and older adults under free versus restricted arm movement positions by sensory condition. Please see Figs. 2 and 3 for graphical representation of balance outcomes.

Condition	Young adults (*n* = 15)		Older adults (*n* = 15)	
	Free	Restricted	Free	Restricted
Normal (FIEO)				
ML-Range (cm)	2.16 ± 0.56	2.46 ± 0.58	2.72 ± 0.57	2.94 ± 0.39
AP-Range (cm)	2.15 ± 0.67	2.44 ± 0.55	2.66 ± 0.93	2.73 ± 0.68
ML-MPF (Hz)	0.37 ± 0.09	0.37 ± 0.11	0.37 ± 0.14	0.39 ± 0.14
AP-MPF (Hz)	0.25 ± 0.10	0.24 ± 0.09	0.28 ± 0.30	0.12 ± 0.13
Proprioceptive dominant (FIEC)				
ML-Range (cm)	3.38 ± 1.11	3.75 ± 1.45	4.10 ± 1.23	5.51 ± 2.61
AP-Range (cm)	3.20 ± 1.01	3.46 ± 1.13	4.05 ± 1.51	4.56 ± 1.85
ML-MPF (Hz)	0.38 ± 0.10	0.38 ± 0.13	0.49 ± 0.13	0.47 ± 0.14
AP-MPF (Hz)	0.29 ± 0.15	0.29 ± 0.09	0.40 ± 0.17	0.39 ± 0.16
Visual dominant (FOEO)				
ML-Range (cm)	3.71 ± 0.72	3.61 ± 0.57	4.73 ± 0.91	6.14 ± 2.04
AP-Range (cm)	3.66 ± 0.77	4.07 ± 0.78	4.76 ± 1.36	5.71 ± 1.19
ML-MPF (Hz)	0.48 ± 0.09	0.49 ± 0.15	0.52 ± 0.08	0.51 ± 0.10
AP-MPF (Hz)	0.31 ± 0.09	0.31 ± 0.11	0.42 ± 0.15	0.44 ± 0.15
Vestibular dominant (FOEC)				
ML-Range (cm)	6.37 ± 1.26	7.85 ± 1.4*	7.39 ± 1.49	11.00 ± 2.81
AP-Range (cm)	7.73 ± 2.04	8.04 ± 1.69	7.82 ± 1.09	9.05 ± 1.67
ML-MPF (Hz)	0.53 ± 0.14	0.62 ± 0.14	0.52 ± 0.07	0.62 ± 0.13
AP-MPF (Hz)	0.48 ± 0.11	0.53 ± 0.09	0.50 ± 0.12	0.57 ± 0.13

AP; anteroposterior, ML; mediolateral, MPF; mean power frequency.*

[1] Note, if better task performance is instead characterised by a *higher* value (e.g., margins of stability, whereby higher values reflect greater postural stability during gait), ARC is instead determined using the following equation: [(restricted arm condition – free arm condition) / free arm condition) * (−100)]

Table 3
Main and interaction effects of the repeated measures ANOVA for standing balance outcomes. Please see Figs. 2 and 3 for graphical representation of balance outcomes.

Outcome	Main effect: Arm movement		Main effect: Sensory condition		Interaction effect: Arm movement × Sensory condition	
	F (1,14)	p (η_p^2)	F (3,42)	p (η_p^2)	F (3,42)	p (η_p^2)
Young adults						
ML-Range	5.788	**0.031 (0.293)**	133.5479	**0.001 (0.905)**	5.253	**0.004 (0.273)**
AP-Range	6.561	**0.023 (0.319)**	157.673	**0.001 (0.918)**	0.068	0.977 (0.005)
ML-MPF	2.216	0.159 (0.137)	19.517	**0.001 (0.582)**	3.238	**0.032 (0.188)**
AP-MPF	0.374	0.551 (0.026)	34.846	**0.001 (0.713)**	1.240	0.307 (0.081)
Older adults						
ML-Range	44.399	**0.001 (0.760)**	83.854	**0.001 (0.857)**	5.571	**0.003 (0.285)**
AP-Range	13.940	**0.002 (0.499)**	160.662	**0.001 (0.920)**	1.848	0.153 (0.117)
ML-MPF	5.243	**0.038 (0.272)**	10.035	**0.001 (0.418)**	6.292	**0.001 (0.310)**
AP-MPF	10.824	**0.005 (0.436)**	8.919	**0.001 (0.389)**	2.108	0.114 (0.131)

AP; anteroposterior, ML; mediolateral, MPF; mean power frequency. Note; $\eta_p^2 \leq 0.12$ indicates small, η_p^2 0.13–0.25 indicates medium, and $\eta_p^2 \geq 0.26$ indicates large effects. Bold values indicate statistically significant effects ($p < .05$).

Table 4
Mean ± SD for ARC outcomes for the young compared to the older adults by sensory condition. Please see Fig. 4 for graphical representation of ARC outcomes.

Condition	Young adults ($n = 15$)	Older adults ($n = 15$)
Normal (%)		
ML-Range	17.5 ± 28.6	11.4 ± 21.3
AP-Range	22.3 ± 45.9	7.0 ± 25.2
Proprioceptive dominant (%)		
ML-Range	13.6 ± 31.4	34.3 ± 51.0
AP-Range	10.7 ± 20.5	20.0 ± 39.9
Visual dominant (%)		
ML-Range	0.24 ± 22.5	32.7 ± 48.7
AP-Range	12.3 ± 15.9	26.9 ± 40.7
Vestibular dominant (%)		
ML-Range	29.8 ± 43.4	55.1 ± 56.0
AP-Range	7.1 ± 22.5	17.8 ± 27.2

AP; anteroposterior, ML; mediolateral, MPF; mean power frequency.

outcomes and Tables 3 and 5 provide the ANOVA outputs for all assessed variables.

3.1. Young adults

3.1.1. ML-Range

As reported in Table 3, there was a significant arm movement × sensory condition interaction ($p = .004$), for ML-Range. Multiple comparisons tests revealed a significant increase in ML-Range from free to restricted arm movement in EC-FO only ($p = .019$, $d = 0.83$). A main effect of arm movement was also observed, with ML-Range greater in the restricted compared to free arm condition ($p = .031$). There was also a significant main effect of sensory condition ($p = .001$), with pairwise comparisons indicating significantly greater ML-Range in EC-FI, EO-FO, and EC-FO (all $p < .001$) compared to EO-FI. AP-Range was also significantly greater in EC-FO compared to EC-FI and EO-FO (both $p =$ .001).

Table 5
Main and interaction effects of the repeated measures ANOVA for arm restriction cost standing balance outcomes. Please see Fig. 4 for graphical representation of ARC outcomes.

Outcome	Main effect: Age		Main effect: Sensory condition		Interaction effect: Age × Sensory condition	
	F (1,28)	p (η_p^2)	F (3,84)	p (η_p^2)	F (3,84)	p (η_p^2)
ML-Range	5.422	**0.027 (0.162)**	3.202	**0.027 (0.103)**	1.401	0.248 (0.048)
AP-Range	28.520	**0.001 (0.505)**	0.273	0.844 (0.010)	1.405	0.247 (0.048)

ARC; arm restriction cost, AP; anteroposterior, ML; mediolateral, Note; $\eta_p^2 \leq 0.12$ indicates small, η_p^2 0.13–0.25 indicates medium, and $\eta_p^2 \geq 0.26$ indicates large effects. Bold values indicate statistically significant effects ($p < .05$).

3.1.2. AP-Range

There was no significant arm movement × sensory condition interaction for AP-Range ($p = .977$). However, there was a significant main effect of arm movement ($p = .023$), with AP-range greater in the restricted compared to free arm condition. A main effect was also observed for sensory condition ($p = .001$), with pairwise comparisons indicating significantly greater AP-Range in EC-FI, EO-FO, EC-FO (all $p < .001$) compared to FI-EO. AP-Range was also significantly greater in EC-FO compared to EC-FI and EO-FO (both $p = .001$).

3.1.3. ML-Frequency

There was a significant arm movement × sensory condition interaction ($p = .032$) for ML-MPF. Multiple comparisons tests revealed a significant increase in ML-MPF from free to restricted arm movement in the vestibular condition only ($p < .001$, $d = 0.64$). Although there was no main effect of arm condition ($p = .159$), there was a main effect of sensory condition ($p < .001$). Pairwise comparisons indicated a significantly greater ML-MPF during EC-FO compared to EO-FI and EC-FI (both $p = .001$). ML-MPF was also significantly greater during EO-FO compared to EC-FI ($p = .050$).

3.1.4. AP-Frequency

With respect to the AP-MPF, there was a main effect of sensory condition ($p < .001$), but the main effect of arm movement ($p = .551$) and the arm movement × sensory condition interaction ($p = .307$) were not significant. Pairwise comparisons indicate significantly greater AP-Range in EC-FO compared to EC-FI and EO-FO (both $p = .001$).

3.2. Older adults

3.2.1. ML-Range

There was a significant arm movement × sensory condition interaction ($p = .003$), for ML-Range. Multiple comparisons tests revealed a significant increase in ML-Range from free to restricted arm condition in the EC-FI ($p = .023$, $d = 0.69$), EO-FO ($p = .018$, $d = 0.89$), and EC-FO ($p < .001$, $d = 1.61$) conditions. A main effect of arm movement was also observed, with ML-Range greater in the restricted compared to free arm condition ($p = .001$). There was also a significant main effect of sensory condition ($p = .001$), with pairwise comparisons indicating significantly greater ML-Range in EC-FI ($p = .003$), EO-FO ($p = .001$), and EC-FO ($p =$ .001) compared to EO-FI. ML-Range was also significantly greater in EC-FO compared to EC-FI and EO-FO (both $p = .001$).

3.2.2. AP-Range

There was no significant arm movement × sensory condition interaction for AP-Range ($p = .153$). However, there was a significant main effect of arm movement ($p = .002$), with AP-range greater in the restricted compared to free arm condition. A main effect was also observed for sensory condition ($p = .001$), with pairwise comparisons indicating significantly greater ML-Range in EC-FI, EO-FO, and EC-FO (all $p < .001$) compared to EO-FI. AP-Range was also significantly greater in EC-FO compared to EO-FO and EC-FO (both $p = .001$).

3.2.3. ML-Frequency

There was a significant arm movement × sensory condition interaction ($p = .001$) for ML-MPF. Multiple comparisons tests revealed a significant increase in ML-MPF from free to restricted arm condition in the vestibular sensory condition only ($p = .003$, $d = 0.96$). A main effect of arm movement was also observed, with ML-MPF greater in the restricted compared to free arm condition ($p = .038$). There was also a significant main effect of sensory condition ($p = .001$), with pairwise comparisons indicating a significantly lower ML-MPF during EO-FI compared to EO-FO ($p = .006$) and EC-FO ($p = .002$).

3.2.4. AP-Frequency

There was no significant arm movement × sensory condition interaction for AP-MPF ($p = .114$). However, there was a significant main effect of arm movement ($p = .005$), with AP-MPF greater in the restricted compared to free arm condition. A main effect was also observed for sensory condition ($p = .001$), with pairwise comparisons indicating a significantly lower AP-MPF during EO-FI compared to EO-FO ($p = .008$) and EC-FO ($p = .001$).

3.3. Arm restriction cost

There were significant main effects of age (ML-Range ARC: $p = .027$; AP-Range ARC: $p < .001$) and sensory condition (ML-Range-ARC: $p = .027$) but no interaction between the two. The main effect of age indicates that ARC-Range were greater in older than young adults. Pairwise comparisons for the main effect of sensory condition indicate a significantly greater ML-Range ARC in EC-FO compared to EO-FI ($p = .034$).

4. Discussion

The primary purpose of this study was to investigate the effects of arm movements on postural control in normal and modified sensory conditions in young and older adults. Our investigation builds on recent literature (i.e., Johnson et al., 2023) with three important new findings. First, in agreement with our hypothesis, we observed that older adults experienced greater postural instability with restricted compared to free arm movements during all modified sensory conditions. Second, in partial agreement with our hypothesis, there was an increase in ML displacement and frequency when arm movements were restricted during only the most challenging (i.e., vestibular dominant) condition in young adults. Third, the main effect of age for ARC outcomes indicates a greater reliance on an upper body strategy in older compared to young adults, independent of the sensory condition, confirming our hypothesis. These collective findings reveal that dependence on upper body movement strategies increases in older adults, independent of sensory availability and/or accuracy.

4.1. The contribution of arm movements to postural control depends upon the availability of sensory information

As expected, there was a main effect of sensory condition in both young and older adults, indicating an increase in both COP displacement and frequency with modified sensory availability. We also observed a significant main effect of arm movement in both groups, which supports previous research reporting greater postural sway during restricted compared to free arm movements conditions in young (Objero et al., 2019; Patel et al., 2014) and older (Johnson et al., 2023) adults. Significant increases in ML COP amplitude under conditions of arm restriction in young adults were restricted to the vestibular-dominant condition, while for older adults, COP amplitude during arm restriction occurred for each sensory restriction. In other words, young compared to older adults adapted to modified sensory information without increasing their reliance on arm movements (likely by 'up-weighting' the other available sensory input [Nashner and Berthoz, 1978]). These results imply that older adults are less able to compensate for the distortion of proprioceptive or visual input using other systems, and therefore implement an adaptive upper body strategy to help correct postural errors. Conversely, young adults can maintain postural stability with arm restriction when vision and proprioception are modified, perhaps due to a higher level of sensory functioning (i.e., no age-related decline). Collectively, our observations indicate that both young and older adults rely on arm movements, but the contribution of an upper body strategy depends upon the characteristics of the available sensory information and/or postural task.

4.2. Increase in COP frequency and amplitude during the vestibular condition

Another notable finding was that arm restriction elicited an increase in both the range and frequency of ML COP displacements under conditions of modified vision and proprioception (i.e., EC-FO: "vestibular dominant"), independent of age. An increase in COP frequency has previously been interpreted as reflecting an increase in stiffness around the ankle joint (i.e., greater co-contraction [Warnica et al., 2014]). We previously reported that a stiffening response assisted young adults to maintain postural performance (COP range) when arm movement was restricted, while such an adaptation provided little assistance for maintaining postural control in older adults (Johnson et al., 2023). We posit that the tendency for an increase in both the amplitude and frequency of ML COP with arm restriction in the vestibular condition may be a failed attempt from the central nervous system to freeze the degrees of freedom in the postural chain (i.e., 'tighter' postural control) in situations of considerable sensory challenge and instability. This greater "co-contraction" (inferred from increased MPF [Winter et al., 1998]) could exacerbate the contribution of arm movement because lower-limb muscles that attempt to restore position of the COM act against highly activated antagonists. In this context, co-contraction appears maladaptive. However, the compensatory use of arm movements appears to be of functional benefit to both young and older adults under conditions of modified vision and proprioception.

4.3. Increased prominence of an upper body movement strategy in older adults

Our hypothesis that the de-stabilising effect of restricted arm movements would be larger in older compared to young adults was confirmed by detecting significant main effects of age for the ML-Range ARC outcome. Our prior work also reported that older, compared to young adults, were more unstable with restricted arm movements, especially when the base of support was narrowed (Johnson et al., 2023). Taken together, the present work supports and extends the notion that older adults may be more reliant on arm movements (based on ML and AP-Range ARC) to correct postural errors during quiet stance, independent of sensory condition. From a model-based perspective, the more prominent effect of arm restriction in older adults could be related to age-related latencies between sensory perception and motor responses, increased sensory noise and greater difficulty with weighting sensory inputs from the lower limbs (Maurer and Peterka, 2005; Wiesmeier et al., 2015). Another potential contributor is the age-related decline in lower-limb force production capacity (Cattagni et al., 2016;

Lord et al., 1991; Lord and Ward, 1994), which may make it harder for the leg muscles to restore the position of the COM after a spontaneous deviation of the body from the vertical (Sarabon et al., 2013). An alternative interpretation that cannot be excluded is the possibility that clasping the hands creates a cognitive "dual task" interference effect. For example, the task of clasping the hands in front of the body may be sufficiently unnatural to cause older adults to allocate greater attentional resources to this "secondary" motor task, resulting in impaired postural control. As dual-task performance was not assessed in the present experiment, future research could investigate the effects of restricted arm movements on postural control during cognitive dual-task conditions.

4.4. Limitations

Although the observations presented here represent a clear advance in knowledge and offer a new perspective on the control of unperturbed upright stance under different sensory conditions, as no quantitative analysis of body kinematics, muscle activation patterns or reflex responses were undertaken, it is difficult to fully understand how upper body strategies were used to correct postural errors during quiet standing. For instance, it is well accepted that clenching one's hands can affect lower limb reflexes (i.e., the 'Jendrassik manoeuvre' [Nardone and Schieppati, 2008]). As such, additional analyses of kinematics and neurophysiologic data would provide more detailed and conclusive information about postural responses and strategies adopted in the young and older age groups. Second, although the study was adequately powered to investigate its hypotheses, the relatively small sample does limit the generalisability of the findings. Studies that replicate and extend our findings in a more functionally diverse group (e.g., fallers vs. non-fallers, frail older adults) would be valuable. Finally, due to the design of the study, in which one balance task follows another (of increasing difficulty) there is a possibility that the results might reflect an order effect. However, we should point out that the order of the arm condition was randomised, and that it is highly unlikely that the order of sensory conditions would have influenced arm contributions to postural control.

4.5. Practical applications

The present findings have some important practical implications from a testing and/or training perspective. Allowing free arm movements is a relatively easy task manipulation that results in improved stability, especially in older adults. Therefore, it might be advisable for fall prevention exercise guideline developers and practitioners to consider exploiting this simple task constraint to improve balance performance during physical training, which may be particularly important for older adults at greater risk of falling. More broadly, fall prevention exercise recommendations for older adults should carefully consider the impact that arm restriction has not only on postural "performance", but also how this task constraint appears to influence specific postural co-ordination strategies to maintain upright stance (i.e., reduced reliance on co-contraction). From a mechanistic training perspective, allowing arm movements may be valuable in acting as a starting point as part of a continuum of balance training to progress to more challenging programs (i.e., restricted arm movements [Hill et al., 2019]). In contrast, it may also be appropriate to restrict arm movements to decrease the moment of inertia to promote more effective control of the COM by focusing on ankle, knee, and hip coordinative strategies. Such distal-proximal strategies may promote a more sensitive anticipatory and/or recovery postural response mechanism. Finally, from a testing perspective, permitting free arm movements is functionally relevant to typical activities of daily living, but it is difficult to control the variability and dynamic nature of how individuals use the arms. In contrast, restricting arm movements is likely to provide a more definite and standardised assessment of lower limb postural function. Finally, we recommend that future research should clearly define and describe arm placement and movement to avoid misinterpretation of balance test outcomes and to facilitate experimental replication.

5. Conclusion

We found that restricting arm movements elicited an increase in ML range and frequency, indicative of a directionally sensitive, destabilising effect. The stabilising effects of free arm movements were greater in older, compared to young adults, which suggests that dependence on upper body movement strategies increases with advancing age. Collectively, these findings show that arm movement strategies appear to compensate for sensory deficits associated with aging, which should be carefully considered when designing and delivering exercise-based fall prevention interventions.

CRediT authorship contribution statement

MH, TM, TE and SL conceived and designed research. MH and EJ conducted experiments. MH performed the analyses and wrote the manuscript. All authors revised and approved the final manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.exger.2023.112338.

References

Agrawal, Y., Carey, J.P., Hoffman, H.J., Sklare, D.A., Schubert, M.C., 2011. The modified Romberg Balance Test: normative data in US adults. Otol. Neurotol. 32 (8), 1309.
Amiridis, I.G., Hatzitaki, V., Arabatzi, F., 2003. Age-induced modifications of static postural control in humans. Neurosci. Lett. 350 (3), 137–140.
Anson, E., Bigelow, R.T., Swenor, B., Deshpande, N., Studenski, S., Jeka, J.J., Agrawal, Y., 2017. Loss of peripheral sensory function explains much of the increase in postural sway in healthy older adults. Front. Aging Neurosci. 9, 202.
Baudry, S., Duchateau, J., 2012. Age-related influence of vision and proprioception on Ia presynaptic inhibition in soleus muscle during upright stance. J. Physiol. 590 (21), 5541–5554.
Blenkinsop, G.M., Pain, M.T., Hiley, M.J., 2017. Balance control strategies during perturbed and unperturbed balance in standing and handstand. R. Soc. Open Sci. 4 (7), 161018.
Boström, K.J., Dirksen, T., Zentgraf, K., Wagner, H., 2018. The contribution of upper body movements to dynamic balance regulation during challenged locomotion. Front. Hum. Neurosci. 12, 8.
Carpenter, M.G., Frank, J.S., Silcher, C.P., Peysar, G.W., 2001. The influence of postural threat on the control of upright stance. Exp. Brain Res. 138 (2), 210–218.
Cattagni, T., Scaglioni, G., Laroche, D., Grémeaux, V., Martin, A., 2016. The involvement of ankle muscles in maintaining balance in the upright posture is higher in elderly fallers. Exp. Gerontol. 77, 38–45.
Choy, N.L., Brauer, S., Nitz, J., 2003. Changes in postural stability in women aged 20 to 80 years. J. Gerontol. A Biol. Sci. Med. Sci. 58 (6), M525–M530.
Di Giulio, I., Maganaris, C.N., Baltzopoulos, V., Loram, I.D., 2009. The proprioceptive and agonist roles of gastrocnemius, soleus and tibialis anterior muscles in maintaining human upright posture. J. Physiol. 587 (10), 2399–2416.
Gatev, P., Thomas, S., Kepple, T., Hallett, M., 1999. Feedforward ankle strategy of balance during quiet stance in adults. J. Physiol. 514 (3), 915–928.
Goble, D.J., Brown, E.C., Marks, C.R., Baweja, H.S., 2020. Expanded normative data for the balance tracking system modified clinical test of sensory integration and balance protocol. Med. Dev. Sens. 3 (3), e10084.
Hébert-Losier, K., 2017. Clinical implications of hand position and lower limb length measurement method on Y-balance test scores and interpretations. J. Athl. Train. 52 (10), 910–917.
Hill, M.W., Wdowski, M.M., Pennell, A., Stodden, D.F., Duncan, M.J., 2019. Dynamic postural control in children: do the arms lend the legs a helping hand? Front. Physiol. 9, 1932.
Horak, F.B., 2006. Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? Age Ageing 35 (suppl_2), ii7–ii11.
Johnson, E., Ellmers, T.J., Muehlbauer, T., Lord, S.R., Hill, M.W., 2023. Exploring how arm movement moderates the effect of task difficulty on balance performance in young and older adults. Hum. Mov. Sci. 89, 103093.
Kuo, A.D., Zajac, F.E., 1993. Human standing posture: multi-joint movement strategies based on biomechanical constraints. Prog. Brain Res. 97, 349–358.
Lee, P.H., Macfarlane, D.J., Lam, T.H., Stewart, S.M., 2011. Validity of the international physical activity questionnaire short form (IPAQ-SF): a systematic review. Int. J. Behav. Nutr. Phys. Act. 8 (1), 1–11.

Lord, S.R., Ward, J.A., 1994. Age-associated differences in sensori-motor function and balance in community dwelling women. Age Ageing 23 (6), 452–460.
Lord, S.R., Clark, R.D., Webster, I.W., 1991. Postural stability and associated physiological factors in a population of aged persons. J. Gerontol. 46 (3), M69–M76.
Maurer, C., Peterka, R.J., 2005. A new interpretation of spontaneous sway measures based on a simple model of human postural control. J. Neurophysiol. 93 (1), 189–200.
Milosevic, M., McConville, K.M.V., Masani, K., 2011. Arm movement improves performance in clinical balance and mobility tests. Gait Posture 33 (3), 507–509.
Morasso, P., 2022. Integrating ankle and hip strategies for the stabilization of upright standing: an intermittent control model. Front. Comput. Neurosci. 16, 956932.
Morasso, P., Cherif, A., Zenzeri, J., 2019. Quiet standing: the single inverted pendulum model is not so bad after all. PLoS One 14 (3), e0213870.
Muehlbauer, T., Heise, J., Hill, M.W., 2022a. Effect of arm movement on balance performance in children: role of expertise in gymnastics. BMC. Res. Notes 15, 363.
Muehlbauer, T., Hill, M.W., Heise, J., Abel, L., Schumann, I., Brueckner, D., Schedler, S., 2022b. Effect of arm movement and task difficulty on balance performance in children, adolescents, and young adults. Front. Hum. Neurosci. 16.
Muehlbauer, T., Hill, M.W., Schedler, S., 2022c. Effect of arm movement and task difficulty level on balance performance in healthy children: are there sex differences? BMC. Res. Notes 15, 362.
Nardone, A., Schieppati, M., 2008. Inhibitory effect of the Jendrassik maneuver on the stretch reflex. Neuroscience 156 (3), 607–617.
Nashner, L., Berthoz, A., 1978. Visual contribution to rapid motor responses during postural control. Brain Res. 150 (2), 403–407.
Objero, C.N., Wdowski, M.M., Hill, M.W., 2019. Can arm movements improve postural stability during challenging standing balance tasks? Gait Posture 74, 71–75.
Patel, M., Magnusson, M., Kristinsdottir, E., Fransson, P.A., 2009. The contribution of mechanoreceptive sensation on stability and adaptation in the young and elderly. Eur. J. Appl. Physiol. 105, 167–173.
Patel, M., Buckwell, D., Hawken, M., Bronstein, A.M., 2014. Does outstretching the arms improve postural stability? Neurosci. Lett. 579, 97–100.
Peterka, R.J., Black, F.O., 1990. Age-related changes in human posture control: sensory organization tests. J. Vestib. Res. 1 (1), 73–85.
Podsiadlo, D., Richardson, S., 1991. The timed “up & go”: a test of basic functional mobility for frail elderly persons. J. Am. Geriatr. Soc. 39 (2), 142–148.
Sarabon, N., Panjan, A., Latash, M., 2013. The effects of aging on the rambling and trembling components of postural sway: effects of motor and sensory challenges. Gait Posture 38 (4), 637–642.
Shumway-Cook, A., Horak, F.B., 1986. Assessing the influence of sensory interaction on balance: suggestion from the field. Phys. Ther. 66 (10), 1548–1550.
da Silva Costa, A.A., Hortobágyi, T., Otter, R.D., Sawers, A., Moraes, R., 2022. Beam width and arm position but not cognitive task affect walking balance in older adults. Sci. Rep. 12 (1), 1–10.
Warnica, M.J., Weaver, T.B., Prentice, S.D., Laing, A.C., 2014. The influence of ankle muscle activation on postural sway during quiet stance. Gait Posture 39 (4), 1115–1121.
Wiesmeier, I.K., Dalin, D., Maurer, C., 2015. Elderly use proprioception rather than visual and vestibular cues for postural motor control. Front. Aging Neurosci. 7, 97.
Winter, D.A., Patla, A.E., Prince, F., Ishac, M., Gielo-Perczak, K., 1998. Stiffness control of balance in quiet standing. J. Neurophysiol. 80 (3), 1211–1221.
Yardley, L., Beyer, N., Hauer, K., Kempen, G., Piot-Ziegler, C., Todd, C., 2005. Development and initial validation of the Falls Efficacy Scale-International (FES-I). Age Ageing 34 (6), 614–619.