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Exploring how arm movement moderates the effect of task difficulty on balance performance in young and older adults

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ABSTRACT

Emerging evidence highlights that arm movements exert a substantial and functionally relevant contribution on quiet standing balance control in young adults. Ageing is associated with “non-functional” compensatory postural control strategies (i.e., lower limb co-contraction), which in turn, may increase the reliance on an upper body strategy to control upright stance. Thus, the primary purpose of this study was to compare the effects of free versus restricted arm movements on balance performance in young and older adults, during tasks of different difficulty. Fifteen young (mean ± SD age; 21.3 ± 4.2 years) and fifteen older (mean ± SD age; 73.3 ± 5.0 years) adults performed bipedal, semi-tandem and tandem balance tasks under two arm position conditions: restricted arm movements and free arm movements. Centre of pressure (COP) amplitude and frequency were calculated as indices of postural performance and strategy, respectively. Especially in older adults, restriction of arm movement resulted in increased sway amplitude and frequency, which was primarily observed for the mediolateral direction. Further, increasing balance task difficulty raised the arm restriction cost (ARC; a new measure to quantify free vs. restricted arm movement differences in postural control) that was more prominent in older adults. These findings indicate the ARC provides a measure of reliance on the upper body for balance control and that arm movement is important for postural control in older adults, especially during tasks of greater difficulty.

1. Introduction

Traditional conceptualisations have viewed the control of quiet stance as involving two distinct modes of operation, referred to as the ankle and hip strategies (Amiridis, Hatzitaki, & Arabatzi, 2003; Gatev, Thomas, Kepple, & Hallett, 1999). The ankle strategy minimises body sway by moving the whole body as single-segment inverted pendulum with counteractive torques at the ankle (Nashner & McCollum, 1985; Morasso, Cherif, & Zenzeri, 2019). In contrast, the hip strategy moves the body as a double-segment inverted pendulum with counterphase motion at the ankle and hip (Amiridis et al., 2003; Kuo & Zajac, 1993). Recent studies also indicate the existence of a complementary ‘upper body strategy’. Empirical support for this strategy is drawn largely from research reporting that postural control during quiet standing declines when the arms are constrained compared to when they are used freely,

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particularly during challenging tasks that threaten balance mediolaterally (i.e., narrow stance) (Hill, Wdowski, Pennell, Stodden, & Duncan, 2019; Muehlbauer et al., 2022; Muehlbauer, Heise, & Hill, 2022; Muehlbauer, Hill, & Schedler, 2022; Objero, Wdowski, & Hill, 2019; Patel, Buckwell, Hawken, & Bronstein, 2014). These collective studies suggest that arm movements serve as an integral component of unperturbed balance performance.

Ageing is associated with a progressive decline in standing postural control (i.e., increase in postural sway) (Sturnieks, St George, & Lord, 2008). This appears to be driven, in part, by a loss of leg proprioception (Anson et al., 2017; Henry & Baudry, 2019) and insufficient torque production by the ankle musculature (Cattagni, Scaglioni, Laroche, Grémeaux, & Martin, 2016; Lord, Clark, & Webster, 1991; Lord & Ward, 1994). To compensate for these lower limb sensorimotor impairments, older adults typically increase their level of ankle muscle co-contraction during standing balance tasks (Benjuya, Melzer, & Kaplanski, 2004; Donath, Kurz, Roth, Zahner, & Faude, 2016; Hortobágyi et al., 2009; Nagai et al., 2011; Vette et al., 2017). However, co-contraction appears more maladaptive than compensatory: it does not lead to reductions in postural sway (Nagai et al., 2011; Warnica, Weaver, Prentice, & Laing, 2014) and may even impede adaptive responses to postural perturbations (Falk et al., 2022; Nelson-Wong et al., 2012). In contrast, the use of an 'upper body strategy' may play a functionally relevant role in helping older adults to compensate for age-related impairments in leg proprioception and muscle weakness. Despite the initial inquiry to investigate the effects of arm movements on postural control in older adults (e.g., da Silva Costa, Hortobágyi, Otter, Sawers, & Moraes, 2022), current interpretations drawn from the literature are limited by the lack of a direct comparison between young and older adults. The use of upper body strategies for the control of balance is often underappreciated, so exploring how this task constraint impacts balance control in older adults is warranted. Thus, the primary purpose of this study was to compare the effects of free versus restricted arm movements on balance performance in young and older adults.

It has been shown that the arms hierarchically complement lower limb postural control mechanisms during challenging mediolateral plane balance tasks (i.e., tandem stance) in young adults (Boström, Dirksen, Zentgraf, & Wagner, 2018; Objero et al., 2019). Although reducing the size of the base of support seems to lead to an increased reliance on an upper body strategy, to build on this work, it is necessary to investigate how the effects of arm movements on balance across different age groups are influenced by increasing the challenge to lateral stability. Accordingly, the second purpose of the current study was to investigate how the effects of age on arm contributions to balance are influenced by (lateral) task difficulty.

In sum, the present study aimed to compare the effects of free and restricted arm movements on postural performance (amplitude of the centre of pressure [COP]) and strategy (frequency of the COP) in healthy young and older adults during tasks of varying degrees of lateral balance difficulty. Our hypotheses were as follows: (1) the amplitude of postural sway would be greater during restricted compared to free arm movement conditions, and this effect would be more pronounced in older compared to young adults and, (2) the increase in sway amplitude with restricted arm movements would be more pronounced for balance tasks with a high difficulty level. Considering that an increase in the mean power frequency (MPF) of the centre of pressure is reliably associated with increased lower limb co-contraction (Warnica et al., 2014) – often interpreted as an ankle "stiffening" response (Adkin & Carpenter, 2018) – we also predict that (3) the frequency of postural sway would be greater during restricted compared to free arm movement conditions.

2. Methods

2.1. Sample size estimation and participants

This was a cross-sectional study with two groups (young [20–35 years] and older [65–80 years] adults). Cohen's *d* effect sizes were calculated from similar studies showing very large mean changes in postural sway between free and restricted arm conditions (Objero et al., 2019 [$d = 1.15$]), differences in postural sway between young and older adults (Hill, Duncan, & Price, 2020 [$d = 1.21$]), and changes in postural sway during tasks of differing difficulty levels (Muehlbauer, Roth, Bopp, & Granacher, 2012 [$d = 3.0$]). Power analysis (G*Power, v3.1.9.4) showed that for a repeated measures ANOVA a minimum of 8 participants per group would be required to detect a significant within-between interaction (group [2] × arm condition [2]) of large effect size (assuming $1\text{-}\beta = 80\%$, $\alpha = 0.05$,

Table 1
Mean ± SD participant characteristic.

	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 (%)	0/0 (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
Grip strength (kg)	37.2 ± 9.1	26.6 ± 10.4	0.006
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
TMT-B (errors)	1.40 ± 1.40	1.33 ± 1.95	0.915

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.

Cohen's $f = 0.40$ [standardised large effect size]) (Faul, Erdfelder, Buchner, & Lang, 2009). A total of 15 young and 15 older adults were recruited for this study (Table 1). All participants were free from any musculoskeletal dysfunction, neurological impairment, or orthopaedic pathology. The experimental procedures were carried out in accordance with the standards outlined in the declaration of Helsinki (1964) and the study received approval by the institutional ethics committee.

2.2. Baseline characteristics

Prior to experimental trials, participants completed baseline assessments, which served to characterise the groups (Table 1). Participants initially completed self-reported questionnaires for physical activity (International Physical Activity Questionnaire [I-PAQ]) (Lee, Macfarlane, Lam, & Stewart, 2011) and concern about falls (16-item Falls Efficacy Scale International [FES—I] (Yardley et al. (2005)). Participants also completed the Timed-Up-and-Go Test (TUG), as described by Podsiadlo and Richardson (1991). The Trail Making Test part B (TMT—B) was chosen to evaluate cognitive function. Finally, the maximum voluntary handgrip strength (kg) was measured using an adjustable hand dynamometer (Lafayette Instrument Company, USA) in a seated position. The dominant hand (determined by self-report) was used for the assessments.

2.3. Experimental procedure

During a single visit to the laboratory, participants completed 30 s standing balance conditions of three progressive difficulties (presented in a randomised order): (1) bipedal stance (right and left hallux and calcaneus together), (2) semi-tandem stance (medial border of the right calcaneus alongside the lateral side of the left hallux), and (3) tandem stance (posterior border of the right calcaneus in front of and touching the anterior border of the left hallux) (Fig. 1). We used these stance manipulations to progressively challenge mediolateral stability and maximise the contribution of the upper body. To ensure consistency between trials, participants stood with the feet positioned over a marked outline for each position. A trial was considered a failure and data collection was stopped if a participants stepped out of position and/or touched something for support. Unsuccessful trials were discarded and repeated until three trials for each condition were successfully recorded. Five older adults were asked to repeat at least one tandem stance trial during both arm conditions due to task failure. 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. restricted), each consisting of three trials for each stance. The order of the two blocks was counterbalanced between participants. Participants completed bipedal, semi-tandem, and tandem balance tasks in a randomised order. Participants could step off the plate and rest between trials (~30 s). Overall, testing of one participant comprised 18 trials with each trial lasting 30 s. The average of each outcome variable for three trials was used for the analysis. During all trials, participants were asked to stand quietly on the force platform while gazing at a black circle (10 cm diameter) 3 m from the force platform, which was adjusted to each individual's eye level. All participants stood barefoot.

2.4. Assessment of standing balance

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 COP parameters. The amplitude (Amp) of displacement of the centre of pressure (COP) 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

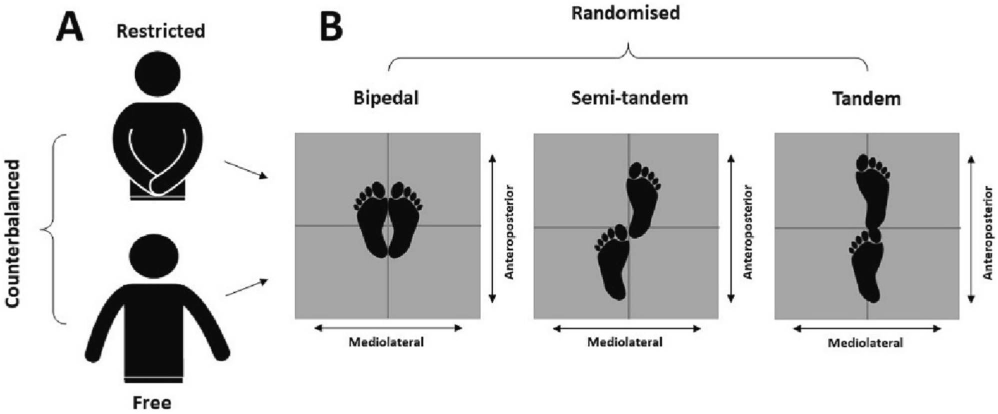

Fig. 1. Schematic diagram of the experimental protocol showing the arm (A) and stance (B) conditions.

stability (Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996). We choose to split the COP into the AP and ML direction, as previous studies (Objero et al., 2019) showed that the amplitude of sway in the ML direction is more affected than in the AP direction by arm movements. Additionally, we were interested in the maximum displacement of the COP as it is generally agreed (Vuillerme, Forestier, & Nougier, 2002) that large COP displacements reflect a shift of the bodies centre of mass closer to the limits of stability which if exceeded may increase the likelihood of a fall and subsequent injury. 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) to provide insight into postural control strategy. MPF was derived following removal of the bias value from the signal. MPF has been viewed as an index of ankle stiffness—the higher the frequency of postural sway, the higher the stiffness around the ankle joint (Warnica et al., 2014). Whilst we acknowledge potential limitations of calculating MPF for 30 s samples (Carpenter, Frank, Silcher, & Peysar, 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 in tandem stance for 60 s would have been too challenging for the older adult participations). However, given that that we were primarily interested in changes in high frequency sway 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.

2.5. *Arm restriction cost*

In the absence of a validated method for objectively measuring the degree to which individuals rely on upper body postural control mechanisms, we propose a new measure for quantifying the difference in performance between free and restricted arm movement conditions, herein described as the ‘arm restriction cost’ (ARC). Similar to the widely reported dual-task cost (Boisgontier et al., 2013; Ellmers, Cocks, Doumas, Williams, & Young, 2016; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003), the ARC quantifies the difference in performance between free and restricted arm movement conditions and yields a single measure rather than utilising restricted and free arm conditions separately. Where better task performance is characterised by a *smaller* value in the outcome variable assessed (e.g., COP amplitude in the present study whereby lower values indicate generally better postural control) the ARC is determined by calculating the percentage change from free to restricted arm movement conditions using the following equation:

$$\left[\left(\text{restricted arm condition–free arm condition}\right)/\text{free arm condition}\ \right)^{*}\ 100\right]$$

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)]

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. To analyse balance and ankle stiffness outcomes, a series of two-way mixed model ANOVAs were undertaken to test for within-subject effects of arm condition (× 2 [free vs. restricted arm movement]) and the between subject effects of group (× 2 [young vs. older adults]). Bipedal, semi-tandem and tandem stance conditions were analysed separately. The ARC outcomes were analysed for our performance outcome (COP amplitude). These were analysed using two-way mixed model ANOVAs for the within-subject effects of stance condition

Table 2
Mean ± SD for all balance outcomes for the young compared to the older adults under free versus restricted arm condition by stance condition.

	Young adults ($n = 15$)		Older adults ($n = 15$)	
	Free	Restricted	Free	Restricted
Bipedal stance				
ML-Amp (cm)	2.30 ± 0.65	2.33 ± 0.64	2.72 ± 0.57	3.54 ± 0.84
AP-Amp (cm)	2.15 ± 0.67	2.28 ± 0.56	2.66 ± 0.93	2.73 ± 0.68
ML-MPF (Hz)	0.31 ± 0.09	0.42 ± 0.10	0.35 ± 0.14	0.44 ± 0.16
AP-MPF (Hz)	0.25 ± 0.11	0.25 ± 0.10	0.27 ± 0.12	0.39 ± 0.19
Semi-tandem stance				
ML-Amp (cm)	2.62 ± 0.35	2.72 ± 0.47	3.81 ± 0.91	5.05 ± 1.63
AP-Amp (cm)	2.34 ± 0.73	2.48 ± 0.82	3.23 ± 1.24	3.76 ± 1.97
ML-MPF (Hz)	0.37 ± 0.13	0.49 ± 0.16	0.40 ± 0.17	0.54 ± 0.16
AP-MPF (Hz)	0.32 ± 0.10	0.33 ± 0.08	0.40 ± 0.18	0.52 ± 0.23
Tandem stance				
ML-Amp (cm)	2.85 ± 0.40	3.58 ± 0.79	4.28 ± 1.10	6.71 ± 2.05
AP-Amp (cm)	2.75 ± 0.84	3.04 ± 1.10	4.39 ± 1.91	4.95 ± 2.27
ML-MPF (Hz)	0.46 ± 0.13	0.62 ± 0.16	0.61 ± 0.12	0.70 ± 0.17
AP-MPF (Hz)	0.39 ± 0.09	0.41 ± 0.15	0.67 ± 0.21	0.80 ± 0.19

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

(× 3 [bipedal vs. semi-tandem vs. tandem stance]) and the between subject effects of group (× 2 [young vs. older adults]). Where significant interactions were detected, post hoc analyses using Bonferroni-adjusted α determined the location of any differences. For the ANOVA tests, effect sizes are reported as partial eta-squared (η_p^2). The p value was a priori set at $p < .05$ for all tests.

3. Results

Table 2 presents the mean values ± SD for all balance outcomes and Tables 3 and 4 provide the ANOVA outputs for all assessed variables.

3.1. Bipedal stance

Amplitude: There was a significant main effect of both group ($p = .001$) and arm condition ($p = .001$), as well as a significant interaction between the two ($p = .002$), with respect to ML-Amp (Fig. 2A and Table 3). Post-hoc tests revealed a significant increase in ML-Amp from free to restricted arm conditions in older adults only ($p < .001$). ML-Amp was also significantly greater in older compared to younger adults in the restricted arm condition ($p < .001$). For the AP-Amp, the main effect of group ($p = .055$) and arm condition ($p = .343$), as well as the interaction between the two ($p = .784$) were not significant (Fig. 2B and Table 3), indicating that the AP-Amp did not change significantly between the free and restricted arm conditions and between young and older adults.

Frequency: With respect to the ML-MPF, there was a main effect of arm condition ($p < .001$), but the main effect of group ($p = .471$) and the group × arm condition interaction ($p = .665$) were not significant (Fig. 2C and Table 3). This indicates that ML-MPF was greater in restricted compared to free arm conditions for both young and older adults. Although the main effect of group was not significant ($p = .078$) there was a main effect of arm condition ($p = .027$) and a significant group × condition interaction ($p = .012$) for the AP-MPF (Fig. 2D and Table 3). Post-hoc tests revealed a significant increase in AP-MPF from free to restricted arm conditions in older adults only ($p = .001$). AP-MPF was also significantly greater in older compared to younger adults in the restricted arm condition ($p = .015$).

3.2. Semi-tandem stance

Amplitude: There was a significant main effect of both group ($p = .001$) and arm condition ($p < .001$), as well as a significant interaction between the two ($p = .004$), with respect to ML-Amp (Fig. 3A and Table 3). Post-hoc tests revealed a significant increase in ML-Amp from free to restricted arm conditions in older adults ($p < .001$). ML-Amp was also significantly greater in older compared to younger adults in the restricted arm condition ($p < .001$). There was a main effect of group ($p = .013$) for the AP-Amp, but the main effect of arm condition ($p = .160$) and the group × arm condition interaction ($p = .412$) were not significant (Fig. 3B and Table 3). This indicates that whilst AP-Amp was greater in older compared to young adults throughout, it did not change significantly between the free and restricted arm conditions in either age group.

Frequency: With respect to the ML-MPF, there was a significant group × arm condition interaction ($p = .001$), but the main effects of

Table 3

Main and interaction effects of the repeated measures ANOVA for all balance outcomes by stance condition.

	Bipedal stance		Semi-tandem stance		Tandem stance	
	F	p (η_p^2)	F	p (η_p^2)	F	p (η_p^2)
ML-Amp						
Group (*young* vs. *older*)	13.698	**0.001** (0.329)	32.164	**0.001** (0.535)	35.982	**0.001** (0.562)
Condition (*free* vs. *restricted*)	13.592	**0.001** (0.327)	14.331	**0.001** (0.339)	40.476	**0.001** (0.591)
Group × condition interaction	11.481	**0.002** (0.291)	10.131	**0.004** (0.266)	11.593	**0.002** (0.293)
AP-Amp						
Group (*young* vs. *older*)	3.997	0.055 (0.125)	7.064	**0.013** (0.201)	11.530	**0.002** (0.292)
Condition (*free* vs. *restricted*)	0.930	0.343 (0.032)	2.087	0.160 (0.069)	2.133	0.155 (0.071)
Group × condition interaction	0.076	0.784 (0.003)	0.693	0.412 (0.024)	0.210	0.650 (0.007)
ML-MPF						
Group (*young* vs. *older*)	0.535	0.471 (0.019)	3.018	0.093 (0.97)	5.626	**0.025** (0.167)
Condition (*free* vs. *restricted*)	24.864	**0.001** (0.470)	3.090	0.090 (0.099)	34.434	**0.001** (0.552)
Group × condition interaction	0.192	0.665 (0.007)	14.755	**0.001** (0.345)	2.745	**0.109** (0.089)
AP-MPF						
Group (*young* vs. *older*)	3.338	0.078 (0.107)	6.353	**0.018** (0.185)	39.612	**0.001** (0.586)
Condition (*free* vs. *restricted*)	5.429	**0.027** (0.162)	9.556	**0.004** (0.254)	6.933	**0.014** (0.198)
Group × condition interaction	7.206	**0.012** (0.205)	6.299	**0.018** (0.184)	3.799	0.061 (0.119)

Amp; amplitude, 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
Main and interaction effects of the repeated measures ANOVA for arm restriction cost by balance outcome.

	Main effect: Age group		Main effect: Stance condition		Interaction effect: Age group × stance condition	
	F	*p* (η_p^2)	*F*	*p* (η_p^2)	*F*	*p* (η_p^2)
Arm restriction cost						
ML-Amp	21.505	**0.001** (0.434)	6.189	**0.004** (0.181)	0.030	0.971 (0.001)
AP-Amp	0.399	0.533 (0.014)	0.579	0.579 (0.019)	0.454	0.638 (0.016)

Amp; amplitude, 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 ($p < .05$).

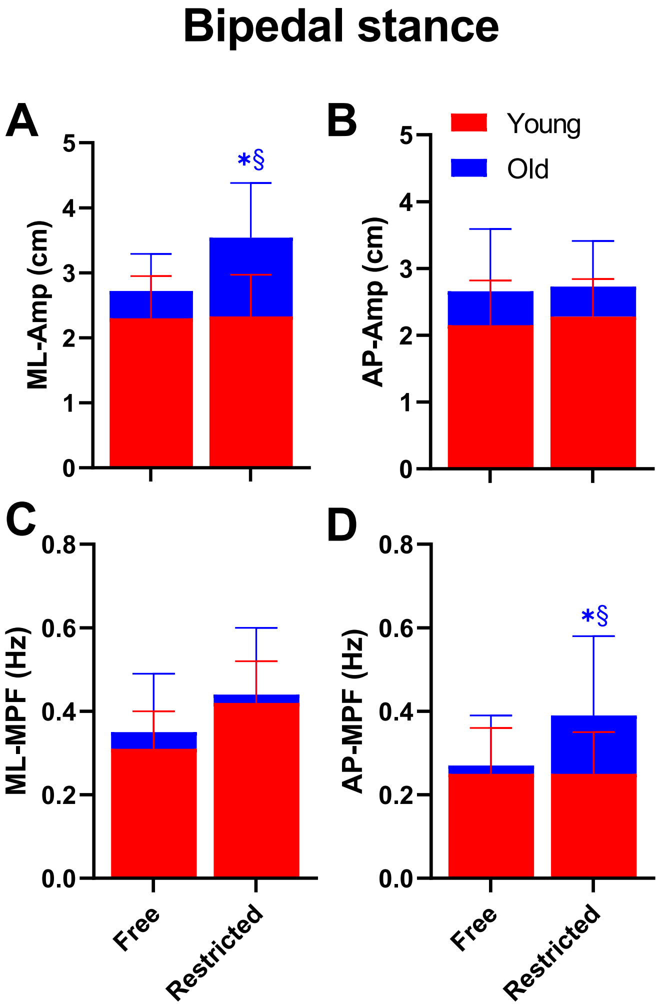

Fig. 2. Mean ± SD balance performance for age group (young vs. older adults) and arm condition (free vs. restricted arm movement) for (A) ML-Amp, (B) AP-Amp, (C) ML-MPF and (D) AP-MPF during bipedal stance. *Significantly different to free arm condition ($p < .05$). §Significantly different to young age group in the same arm condition ($p < .05$).

arm condition ($p = .090$) and group ($p = .093$) were not significant (Fig. 3C and Table 3). Post-hoc tests revealed a significant increase in ML-MPF from free to restricted arm conditions in older adults ($p < .001$). ML-MPF was also significantly greater in older compared to younger adults in the restricted arm condition ($p = .003$). For the AP-MPF, the main effect of group ($p = .018$) and arm condition ($p = .004$), as well as the interaction between the two ($p = .018$) were significant (Fig. 3D and Table 3). Post-hoc tests revealed a significant increase in AP-MPF from free to restricted arm conditions in older adults ($p < .001$). AP-MPF was also significantly greater in older compared to younger adults in the restricted arm condition ($p = .005$).

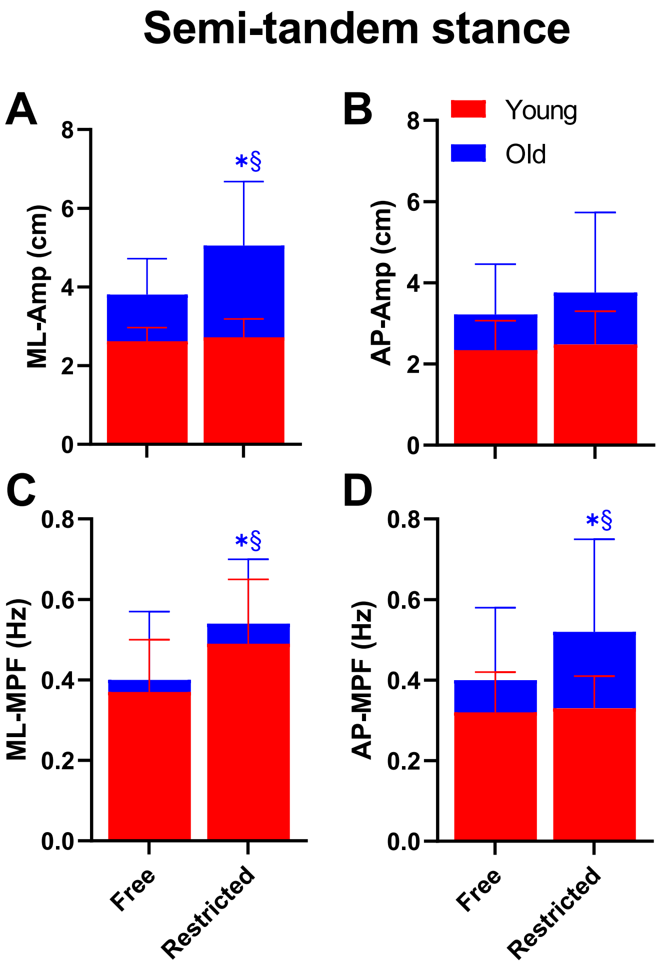

Fig. 3. Mean ± SD balance performance for age group (young vs. older adults) and arm condition (free vs. restricted arm movement) for (A) ML-Amp, (B) AP-Amp, (C) ML-MPF and (D) AP-MPF during semi-tandem stance. *Significantly different to free arm condition ($p < .05$). §Significantly different to young age group in the same arm condition ($p < .05$).

3.3. Tandem stance

Amplitude: There was a significant main effect of both group ($p < .001$) and arm condition ($p < .001$), as well as a significant interaction between the two ($p = .002$), with respect to ML-Amp (Fig. 4A and Table 3). Post-hoc tests revealed a significant increase in ML-Amp from free to restricted arm conditions in both older ($p < .001$) and young ($p = .046$) adults. ML-Amp was also significantly greater in older compared to younger adults in both restricted and free arm condition (both $p < .001$). With respect to the AP-Amp, there was a main effect of group ($p = .002$), but the main effect of arm condition ($p = .155$) and group × arm condition interaction ($p = .650$) were not significant (Fig. 4B and Table 3). As with semi-tandem, AP-Amp was greater in older compared to young adults during both free and restricted arm conditions.

Frequency: With respect to the ML-MPF, there was a main effect of group ($p < .001$) and arm condition ($p = .025$), but the group × arm condition interaction ($p = .109$) was not significant (Fig. 4C and Table 3). This indicates that ML-MPF was greater in older compared to young adults throughout, and in the free compared to the restricted arm condition (for both groups). For the AP-MPF, there was a main effect of group ($p < .001$) and arm condition ($p = .014$), and the interaction between the two was not significant ($p = .061$) (Fig. 4D and Table 3). This indicates that AP-MPF was greater in older compared to young adults, and in the free compared to the restricted arm condition.

3.4. Arm restriction cost (ARC)

Although there was a significant main effect of group ($p < .001$) and stance condition ($p = .004$) (Fig. 5A and Table 4) for ML-Amp ARC, the group × stance condition interaction was not significant ($p = .971$). The main effect of group indicates that the ML-Amp ARC was greater in older than young adults throughout. ML-Amp ARC was also greater during semi-tandem compared to bipedal stance (p

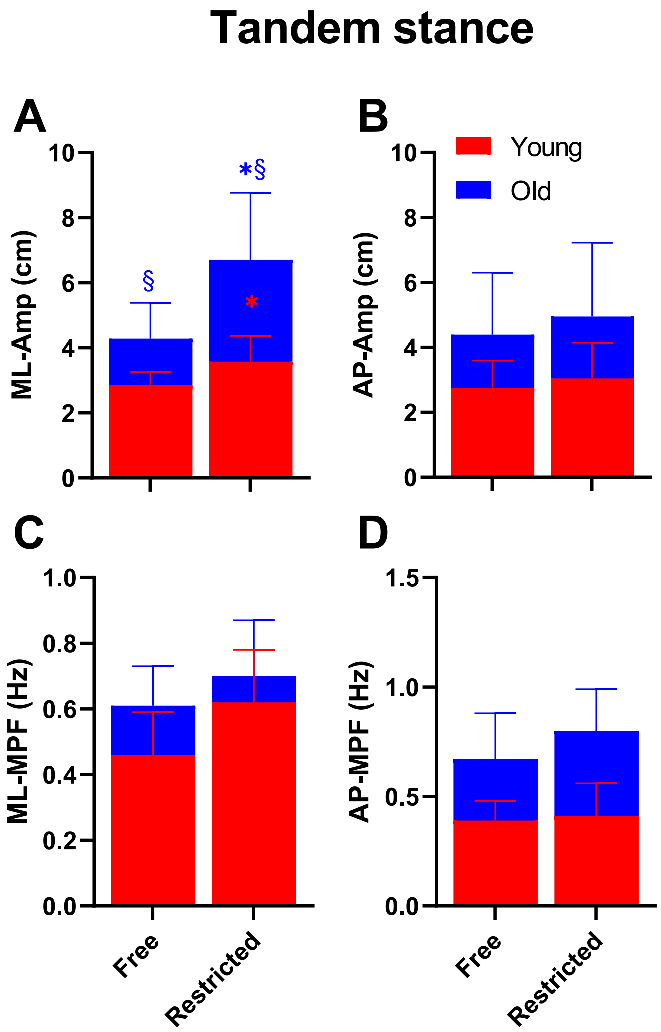

Fig. 4. Mean ± SD balance performance for age group (young vs. older adults) and arm condition (free vs. restricted arm movement) for (A) ML-Amp, (B) AP-Amp, (C) ML-MPF and (D) AP-MPF during tandem stance. *Significantly different to free arm condition ($p < .05$). §Significantly different to young age group in the same arm condition ($p < .05$).

= .029) and greater during tandem compared to semi-tandem stance ($p = .014$) for both groups. With respect to the AP-Amp ARC, neither the main effect of group ($p = .533$) or stance condition ($p = .579$), as well as the group × stance condition ($p = .454$), were significant (Fig. 3B and Table 4).

4. Discussion

We aimed to elucidate age-related differences in the effects of restricted arm movements on postural control. Three new findings emerged from this investigation: (1) in accordance with our first hypothesis, our results on sway amplitude showed that older adults were more unstable with restricted arm movements, with these effects most prominent in the medio-lateral plane; (2) restricted arm movements elicited an increase in sway frequency (suggesting an ankle stiffening responses) in nearly all conditions in both young and older adults, although this stiffening strategy appears to have assisted only the young adults to maintain postural performance; and (3) the ARC – a new measure that may identify individuals that rely more on upper body movement to control postural stability – can discriminate between age and task difficulty for postural performance (ML sway amplitude).

4.1. Effects of arm restriction on postural control

As predicted, and in accordance with previous literature (i.e., Objero et al., 2019), restricting arm movements resulted in an increased sway amplitude (especially for the ML direction) during standing balance tasks in young and older adults, and was more pronounced in the older cohort. The observation that older adults place greater dependence on an “upper body strategy” to maintain

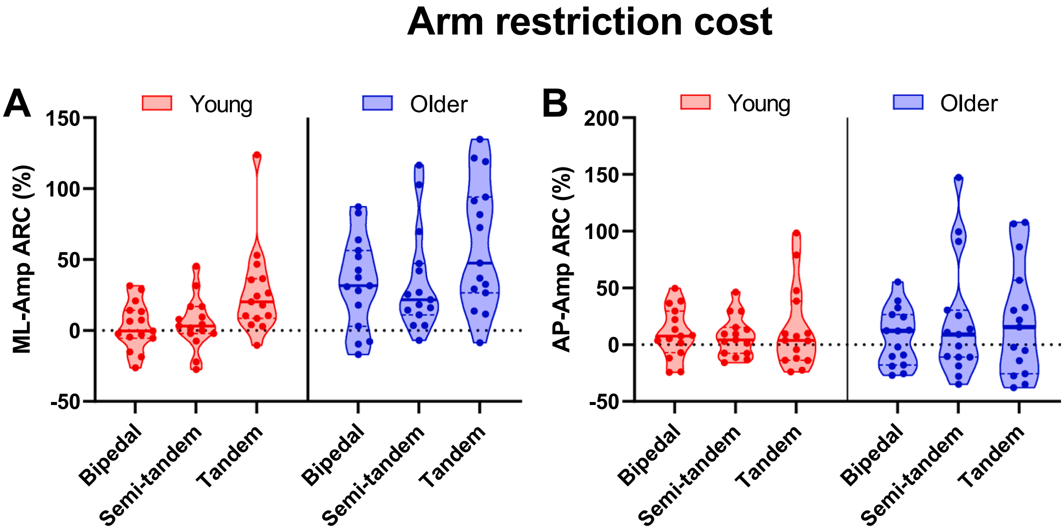

Fig. 5. Violin plots of the arm restriction cost (ARC) for age group (young vs. older adults) and stance condition (bipedal vs. semi-tandem vs. tandem stance) for (A) ML-Amp, (B) AP-Amp. Each violin represents the median (centre line), 25th% (bottom of the box) and 75th% (top of the box) percentile.

quiet stance could be attributed to several factors related to age-related decrements in musculoskeletal capacity and sensory function of the lower limbs. We speculate that the absence of reliable proprioceptive cues from the lower limbs (Anson et al., 2017; Henry & Baudry, 2019), delays in the transmission of lower limb sensory feedback (Ozdemir, Contreras-Vidal, & Paloski, 2018) and an impaired ability to generate appropriate torques at the ankle joint (Cattagni et al., 2016; Lord et al., 1991; Lord & Ward, 1994) could be driving such greater reliance on upper body movements. This interpretation is consistent with the idea that the control of upright stance shifts from a proximal (i.e., ankle) strategy in young adults to a more distal (i.e., hip) strategy in older adults (Amiridis et al., 2003).

Another striking result was that restricted arm movements elicited an increase in the frequency of postural sway – a behaviour that is often associated with increased ankle stiffness (Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998) – in nearly all conditions, in both young and older adults. When combined with the sway amplitude responses, these findings imply that a stiffening strategy (presumably an attempt to provide more joint stability and maintain a tighter control of the centre of mass within the boundaries of the base of support) was sufficient to maintain postural performance in young adults during the easy to moderate difficulty tasks (i.e., no changes in sway amplitude between free vs. restricted arm conditions). In contrast, the stiffness strategy observed in older adults did not lead to any functional maintenance in sway amplitude. Our result of greater sway frequency and amplitude during restricted arm conditions appears to be consistent with the idea that greater ankle muscle co-contractions may have limited functional benefit for older adults (Vette et al., 2017; Warnica et al., 2014).

4.2. Moderating effects of task difficulty

A notable finding in the present study was that the effect of arm movement restriction was more pronounced for balance tasks with a high difficulty level, confirming our second hypothesis. More specifically, greater ML-Amp ARC values were observed when balance task difficulty was systematically increased. Several previous studies have reported that arm contribution increases when the balance task becomes more challenging in children (Muehlbauer, Heise, & Hill, 2022) and young adults (Boström et al., 2018; Objero et al., 2019; Patel et al., 2014). One possible explanation for this finding is that an upper body strategy may be expected to be employed when the support surface becomes progressively narrow in which only little ankle torque can be applied. In agreement with this idea, previous studies have suggested that in challenged balance situations the arms serve as a counterweight to shift the body COM away from the direction of instability (Marigold, Bethune, & Patla, 2003), generate restoring torque to reduce angular momentum of the body (Patel et al., 2014) and increase the moment of inertia (Hill et al., 2019). Although upper limb strategies are clearly employed to maintain quiet standing balance, no quantitative movement analysis was undertaken and therefore this study cannot comprehensively contribute to understanding upper body strategies used for maintaining quiet standing balance performance. Future research which examines upper limb kinematics would be valuable in this regard.

In addition to the main effect of task difficulty, we also observed a main effect of group, indicating that the ML-Amp ARC was greater in older than young adults. Taken together, the present findings indicate that older adults, in particular, benefit from arm movements during quiet stance balance assessments with a high difficulty level. Our interpretation of this finding is that the ML-Amp ARC is a simple and easy to calculate measure to quantify the extent to which individuals rely on upper body postural control mechanisms, which is sensitive to both age and balance task difficulty.

5. Conclusion

The present work provides novel insights into differential contributions of arm movements on postural control in young and older adults. The findings presented here provide strong support for an “upper body strategy” complimenting lower limb postural control mechanisms, particularly in older adults. A stiffening response (indicated by increased sway frequency) appears to have assisted young adults to maintain postural performance in bipedal and semi-tandem stance when arm movement was restricted. In contrast, a stiffening strategy provided little assistance for maintaining postural control in older adults in challenging balance conditions.

Author statement

MH, TE, TM and SL designed the research. MH and EJ conducted data collection. MH analysed the data and wrote the manuscript. MH, TE, TM and SL revised the manuscript. All authors read and approved the final manuscript.

Data availability

Data will be made available on request.

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