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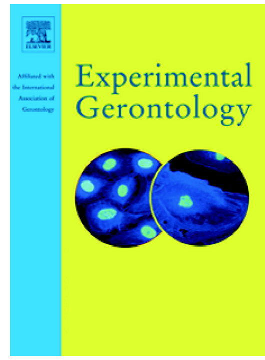

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The emergence of age-related deterioration in dynamic, but not quiet standing balance abilities among healthy middle-aged adults

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ABSTRACT

The purpose of the present study was to quantify differences in lower extremity reach performance, static posturography and gait outcomes between young (20 – 39 years), middle-aged (40 – 59 years) and older (60 – 79 years) adults using identical tests and parameters. This was a cross-sectional study with three parallel groups (young [20-39 years] vs. intermediate [40 – 59 years] vs. older [60-79 years] adults). In a randomised order each participant completed: (i) static posturography, (ii) lower extremity reach performance, and (iii) gait assessment. Changes in balance between age groups were analysed using analysis of variance (ANOVA). Additionally, correlational analysis was used to identify relationships between age and outcome measures. Centre of pressure (COP) movement was greater in older compared to intermediate-aged (d= 0.50 – 2.40) and young (d= 0.54 – 2.61) adults (p<0.001). Reduced lower extremity reach distance was found in older compared to intermediate-aged (d= 1.28 – 3.60) and young (d= 2.09 – 3.87) adults (p<0.001), whilst young adults demonstrated greater reach distances than intermediate (d= 0.64 – 1.74) aged adults (p<0.001). Correlational analysis revealed moderate to strong positive correlations between age across the adult life span (20 –

79 years) for all COP metrics and lower extremity reach outcomes. When correlational analyses were performed only in the young and middle-aged groups (20 – 59 years), coefficients were weak and not significant for the COP, but remained moderate for lower extremity reach performance. Lower extremity reach performance reveals earlier age-related declines in postural stability that are not evident during quiet standing tasks of varying difficulty. These findings should contribute to the early identification of potential balance deficits in those where balance problems do not yet exist, which will assist clinical decision making with respect to timely implementation of fall prevention strategies.

KEYWORDS: Functional tasks · Mobility · Centre of pressure · Aging · Fall-risk

1. INTRODUCTION

Falls represent a substantial public health problem affecting at-least one-third of people aged 65 years and older (Rubenstein, 2006). Efforts to elucidate risk factors for falls have subsequently intensified in recent years. Whilst the etiology of falling is multifaceted, balance and mobility performance appear to be potentially modifiable factors that may reduce fall risk (Johansson et al. 2017; Piirtola and Era, 2006). Consequently, early detection of changes in balance abilities is crucial to ensure that fall prevention strategies may be considered for implementation to target specific impairments to decrease the risk of falling.

The ideal balance screening measurements should be quick and simple to administer, provide easily interpretable results and be adequately sensitive to reveal incipient deterioration in balance control (Riemann et al. 2019). Many falls occur during ambulatory tasks, such as walking or transfers (Talbot et al. 2005). It is therefore not surprising that in the community setting, fall risk is often determined by functional mobility assessments (i.e. gait speed or timed-up-and-go) (Schoene et al. 2013 Bohannon, 1997). However, functional assessments are typically subjective, show ceiling effects, are somewhat rudimentary and usually lack the ability to capture balance impairment at its early phase (Mancini and Horak, 2010; Pajala et al. 2008).

In the laboratory setting, postural instability is investigated using objective measures of posturography (Paillard & Noe, 2015), the advantages of which over functional assessments include the avoidance of subjective scoring systems and greater sensitivity to small changes (Mancini and Horak, 2010; Visser et al. 2008). Increases in the displacement and velocity of the centre of pressure (COP) are indicative of poor balance (Roman-Liu, 2018) and can prospectively predict future falls (Johansson et al. 2017; Pajala et al. 2008; Piirtola and Era, 2006). However, assessment of quiet stance lacks ecological validity (Visser et al. 2008), often demonstrates substantial inter-subject and intra-subject variability (Geurts et al. 1993), requires expensive equipment (Riis et al. 2020), may not adequately stress our postural control system (Clifford and Holder-Powell 2010) and represents a relatively small subset of our balance repertoire (Visser et al. 2008). These limitations may also result in failure to discriminate between individuals with different levels of fall risk. Despite the variety of posturographic and functional tools that assess balance ability, there is still a need for screening procedures that combine accurate and sensitive objective assessment with inexpensive and easy to administer evaluations. Without examining this public health professionals may make erroneous decisions in regard to individuals who may have increased fall risk.

Lower extremity reaching performance as measured using the Star Excursion Balance Test (SEBT) has been reported to involve elevated physical demands (e.g. increased requirement for muscle force production) beyond those of quiet standing tasks (Norris and Trudelle-Jackson, 2011). The increased challenge of these tasks may reveal age-related declines in balance that are not evident during quiet standing tasks (Matson and Schinkel-Ivy, 2020). The patterns of age-related decline, and the age at which decreases in SEBT performance can first be detected, have not been investigated. While lower extremity reaching performance (i.e. Y-Balance Test [YBT]) has been reported in young (Coughlan et al. 2008), middle-aged (Bouillon and Baker, 2011; Freund et al. 2018) and older (Freund et al. 2018; Sipe et al. 2019) adults, full synthesis of the age-related changes across studies is difficult because of methodological inconsistences and variations in the balance tasks and outcome measures utilised.

The purpose of the present study was to quantify differences in lower extremity reach performance, static posturography and gait outcomes between young (20 – 39 years), middle-age (40 – 59 years) and older (60 – 79 years) adults using identical tests and parameters. Given that increases in postural sway (Era et al. 2006) and mobility (Isles et al. 2004) are already present among young

(30s) and middle-aged (40s) adults, respectively, it was hypothesised that declines in lower extremity reach performance would first emerge in middle-aged (40 – 59 years) adults, with further reductions in performance presenting in the older age decades (60 – 79 years). Furthermore, in an effort to obtain a clear and more integrated insight into the nature of how balance and gait function declines across different ages, examination of individual data was performed using correlational analysis between age and balance performance.

2. METHODS

2.1 Sample size estimation

This was a cross-sectional study with three parallel groups (young [20 – 39 years] vs. intermediate [40 – 59 years] vs. older [60 – 79 years] adults). Effect sizes (Cohen's *d*) were calculated from similar studies from mean differences in the mean COP velocity while standing on a firm surface with eyes open ($cm \cdot s^{-1}$) ($d = 0.55$) (Choy et al. 2003), maximal gait velocity ($m \cdot s^{-1}$) ($d = 2.03$) (Bohannon, 1997) and the coefficient of variation (%) of double support time ($d = 1.59$) (Menant et al. 2009) between young (20's) and older (60's) adults. Sample size was estimated using an *a priori* power analysis (G* Power software [Version 3.1.9.4]) for the mean COP velocity while standing on a firm surface with the eyes open (i.e. variable with the smallest effect size to avoid bias) (statistical power = 0.95, alpha = 0.05, effect size = 0.55) and revealed that a total of 51 participants would be sufficient to detect significant differences in outcome measures between young and older adults (Faul et al. 2009).

2.2 Participants

To account for possible attrition, twenty young adults (female/male; 10/10, age; 28.4 ± 5.0 years, height, 1.72 ± 0.07 m, mass; 72.6 ± 12.2 kg, BMI, 24.5 ± 3.2 kg/m^2), twenty intermediate-aged adults (female/male; 10/10, age; 47.0 ± 5.5 years, height, 1.72 ± 0.07 m, mass; 75.7 ± 14.5 kg, BMI, 25.6 ± 4.1 kg/m^2) and twenty older adults (female/male; 11/9, age; 69.8 ± 6.5 years, height, 1.62 ± 0.09 m, mass; 71.6 ± 16.4 kg, BMI, 26.9 ± 4.5 kg/m^2) were recruited. Prior to any involvement, participants gave their written informed consent to participate in this study. Participants in the young and intermediate age group were recruited from the University student and staff population. Older adults were recruited from the local community. The study was approved by the institutional ethics committee and all experimental procedures were carried out in accordance with the standards outlined in the Declaration of Helsinki (1964). Participants completed a pre-screening medical questionnaire to detect potential risk factors that might affect their ability to balance. The only criteria for inclusion was the ability to walk 10 m independently without an assistive device. Exclusion criteria were as follows; neurological impairment that may affect balance, self-reported fall within the last year, cardiovascular or pulmonary diseases, orthopaedic pathology, musculoskeletal dysfunctions or lower limb surgery within the previous 12 months.

2.3 Experimental procedures

Each participant visited the biomechanics laboratory on three occasions separated by a minimum of 24 hours and maximum of 72 hours. Participants completed; (1) posturographic assessment, (2) lower extremity reaching assessment, and (3) gait assessment, with each session lasting between 15-45 min. We avoided multiple tests within the same session because of the potential for cumulative fatigue effects on balance performance. The order of tests was randomised both within and between sessions. Participants were asked to avoid strenuous exercise 48 h prior to testing and not to change their usual physical activity levels. Adherence to these guidelines was confirmed verbally prior to each assessment session. The same investigator carried out all procedures with all participants at the same time of day (±1 hr).

2.4 Quantitative posturography

To examine centre of pressure (COP) movements during upright bipedal stance, each participant stood barefoot on a force platform (AMTI, AccuGait, Watertown, MA) for 30 s. Each participant completed the following standing balance tasks in a randomised order: (1) bipedal stance on a firm surface with the eyes open (EO) and (2) eyes closed (EC), (3) bipedal standing on a foam balance pad (Balance-pad Plus, Alcan Airex AG, Switzerland) with EO, (4) and EC, (5) dominant unipedal stance and (6) non-dominant unipedal stance on a firm surface. These combinations of sensory modulation (i.e. foam surface, eyes closed) have been shown to increase the level of difficulty of standing balance tasks, as deduced by varying degrees of COP movement and muscle activity (Donath et al. 2016). To ensure continuity between trials, unshod foot position was standardised at a distance of 3 cm between the medial extremities of the posterior side of the calcaneus with feet abducted at 30º, as determined at the medial extremity of the great toe. During unipedal trials, participants were instructed that the unloaded leg should not touch the supporting leg and the knee should be flexed to 90º. Termination of the test was recorded if; (1) the foot touched the support leg, (2) hopping occurred, (3) the foot touched the floor, (4) the arms touched something for support. During all trials, participants were asked to stand as still as possible on the force platform, with the arms clasped in front of their body (Objero et al. 2019), while gazing at a target 1.5 meters from the force platform, which was adjusted to the eye level of each individual. Participants practiced each postural task once prior to recorded trials. A total of three trials were recorded consecutively for each condition and the mean of these trials was used in subsequent analysis. Participants could *step off* the plate and rest between tests (±1 min). Data were sampled at 100 Hz (AMTI, Netforce, Watertown, MA) and the total amplitude of the centre of pressure (COP) displacement in the anteroposterior (COP_{AP}) and mediolateral (COP_{ML}) directions (both cm), and mean COP velocity ($cm{\cdot}s^{-1}$) were subsequently calculated (AMTI, BioAnalysis, Version 2.2, Watertown, MA) and served as indirect measures of postural sway. The amplitude of displacement reflects the distance between the maximum and minimum COP displacement for each direction (where the greater the value, the worse the postural stability) while the mean COP velocity reflects the efficiency of the postural control system (the smaller the velocity, the better the postural control) (Paillard and Noe, 2015). The validity and reliability of these parameters have previously been established for this sampling duration (Pinsault & Vuillerme, 2009).

2.5 Lower extremity reach performance

Lower extremity reaching performance of the right and left limb was determined using the Star Excursion Balance Test (SEBT) (Gribble and Hertel, 2003). Participants stood barefoot on a single limb with their metatarsophalangeal joint on the centre of centre of a grid marked out on the laboratory floor using highly visual adhesive tape. The first two lines formed the horizontal and vertical axes, and a further two lines were positioned perpendicular to each other at 45° increments from the centre of the grid. The SEBT consists of eight reach directions; anterior (ANT), anterolateral (AL), lateral (LAT), posterolateral (PL), posterior (POS), posteromedial (PM), medial (MED), and anteromedial (AM). Following familiarisation (three practice attempts in each direction), participants performed three reaches in each direction. While maintaining a single limb stance, participants were asked to push a target (reach indicator) along the line with the contralateral limb in each direction. Maximal reach distance was measured by reading the tape measure at the edge of the reach indicator, reflecting the point where the most distal part of the foot reached. Participants were instructed to be able to move their arms freely during the tasks (Hill et al. 2019). The trial was discarded and repeated if the participant (1) failed to maintain single limb stance (i.e., touch the floor with the reach limb), (2) failed to remain in contact with the reach indicator at the most distal point (i.e., kicked the reach indicator to achieve greater distance), (3) used the reach indicator to support weight (i.e., mechanical support) or (4) failed to return to the reach foot at the centre of the foot plate. Although the reach direction was randomised, to improve reproducibility of the testing protocol, participants performed three consecutive reach attempts for each direction. The greatest reach distance for each direction was used for subsequent analysis. Reach distance was normalised to limb length (reach distance / limb length * 100). Each participant's dominant limb length was measured in centimetres from the anterior superior iliac spine to the most distal portion of the medial malleolus using an anthropometric measuring tape (Gribble and Hertel, 2003).

2.6 Gait assessment

Gait velocity was recorded on an 8-m walkway, with an additional 2 m acceleration and deceleration zone at each end. Times were recorded to the nearest millisecond using photoelectric timing gates (SmartSpeed, Fusion Sports, Australia), and later transformed to meters per second ($m \cdot s^{-1}$). Comfortable gait velocity was assessed by instructing participants to walk at a preferred pace, at "the speed which you would walk to the shops". Maximal gait velocity was assessed by asking participants to walk as "fast as possible, without running". Comfortable and maximal gait velocity were each recorded three times. The average and fastest time, respectively, were used for subsequent analyses. Two force platforms (AMTI, AccuGait, Watertown, MA) embedded in the laboratory floor were used to record ground reaction forces of each foot during a single gait cycle during three additional comfortable walking speed trials. Consecutive force platform strikes of the right and left foot were subsequently acquired. To ensure valid data acquisition each participant's starting position was adjusted until the right foot contacted the platform first followed by the left foot without any visible or self-reported alteration in normal gait. All participants were asked to remove footwear. In the case of the participant missing the force platform, partially or completely, or if both feet come into contact with the same platform, the trial was discarded. If trials were repeatedly unsuccessful participants were instructed to start the gait initiation from a different location along the walkway. This procedure was repeated until three valid trials were recorded. Ground reaction forces were sampled at 200 Hz, enabling the acquisition of double-limb support time (sec). The double limb support time was calculated as the absolute time (in sec) that both feet were in contact with the ground from when the swinging leg meets the ground (front foot heel strike) to when the support leg leaves the ground (contra-lateral foot toe off). We calculated the mean double limb support time because age-related difference has been observed for this metric (Prince et al. 1997) and double limb support time closely reflects balance control mechanisms (Gabell and Nayak, 1984). The coefficient of variation (CV; [SD/Mean]*100) was also calculated for double-limb support time to assess gait variability, a marker of gait instability and fall-risk (Verghese et al. 2009). An average of three trials was used in subsequent analysis.

2.7 Statistical analysis

Data were analysed using SPSS version 25.0 (IBM Inc., Chicago, IL). Box and whisker plots with individual values was used to show the degree of dispersion and skewness in the data and to identify potential outliers. For all analyses, normality (Kolmogorov–Smirnov Test) and homogeneity of variance (Levene's Test) were performed and confirmed prior to parametric tests. If data were not normally distributed, a non-parametric tests (Welch Test) was used to analyse differences between age groups. If data were normally distributed, separate one-way analysis of variance (ANOVA) was used to assess differences in COP movements, SEBT and gait outcome measures between the three age groups. Tukey's Honestly Significant Differences (HSD) test was used for post hoc comparisons.

Effect sizes are reported as Cohen's *d* for pairwise comparisons, with 0.2, 0.6, 1.2 and 2.0 indicating small, medium, large and very large effects, respectively (Hopkins et al. 2009). The associations between age and balance/gait performance were examined through Pearson's product moment correlation and reported as the correlation coefficient (*r* value). Coefficient values were interpreted as small (r = 0.10 to 0.30), moderate (r = 0.30 to 0.50) and large (r = 0.50 to 1.0). We performed the correlational analysis on both the whole group (n = 60, 20 – 79 years) or only the young and middle-aged adults (n = 40, 20 – 59 years). This approach allowed us to determine whether the correlation of balance with age across the adult lifespan (20 – 79 years), were driven by changes in old age, or emerged in the middle-age groups. The alpha value was a priori set at $p < 0.05$ for all analyses.

3. RESULTS

3.1 Centre of pressure movement

Figure 1 illustrates age related differences in COP measures when standing with the eyes open and eyes closed on a fixed and foam surface. Main effects of age were detected for all COP measures (p<0.001). Post-hoc between-subject analyses revealed statistically greater COP amplitudes (anteroposterior and mediolateral) and mean COP velocity in older compared to intermediate-aged (d= 0.79 – 2.40) and young (d= 1.21 – 2.61) adults (p<0.001). There were no differences in any COP measures between young and intermediate-aged adults (p>0.05).

***** FIGURE 1 ABOUT HERE *****

Figure 2 illustrates age related differences in COP measures of postural sway when standing on the right and left limb. Main effects of age were detected for anteroposterior COP amplitude and mean COP velocity (p<0.001). Post-hoc between-subject analyses revealed statistically greater anteroposterior COP amplitude and mean COP velocity in older compared to intermediate-aged (p<0.001, d= 0.50 – 1.28) and young (p<0.001, d= 0.54 – 1.39) adults. There were no differences in any COP measures between young and intermediate-aged adults (p>0.05).

***** FIGURE 2 ABOUT HERE *****

3.2 Lower extremity reach performance

Figure 3 illustrates age related differences in SEBT performance with right foot stance. Main effects of age were detected for all reach directions ($p<0.001$). Post-hoc between-subject analyses revealed statistically greater reach distances in young adults compared to intermediate ($d= 0.71 – 1.74$) and older ($d= 2.09 – 3.87$) age groups ($p<0.001$). Additional post-hoc analyses revealed statistically greater reach distances in the intermediate group compared to older ($d= 1.28 – 2.09$) adults ($p<0.001$).

***** FIGURE 3 ABOUT HERE *****

Figure 4 illustrates age related differences in SEBT performance with left foot stance. Main effects of age were detected for all reach directions ($p<0.001$). Post-hoc between-subject analyses revealed statistically greater reach distances in young adults compared to intermediate ($d= 0.64 – 1.10$) and older ($d= 2.70 – 3.60$) age groups ($p<0.001$). Additional post-hoc analyses revealed statistically greater reach distances in the intermediate group compared to older ($d= 1.33 – 2.52$) adults ($p<0.001$).

***** FIGURE 4 ABOUT HERE *****

3.3 Gait assessment

Figure 5 illustrates age related differences in gait outcomes. Main effects of age were detected for all gait measures ($p<0.001$). Post-hoc between-subject analyses revealed a statistically faster comfortable ($p= 0.014$, $d= 0.97$) and maximal ($p<0.001$, $d= 3.88$) gait speed in young compared to older adults. Additional post-hoc analyses revealed a statistically faster maximal gait speed in young compared to intermediate-aged adults ($d= 1.13$), whilst the intermediate group were significantly faster than the older group ($d= 1.95$) ($p<0.001$). Post-hoc between-subject analyses revealed a statistically greater double limb support time in older adults compared to young ($d= 1.51$) and intermediate ($d= 1.62$) age groups ($p<0.001$). Similarly, the coefficient of variation of the double limb support time was statistically greater in older compared to young (*d*= 2.32) and intermediate (*d*= 1.70) age groups ($p<0.001$).

***** FIGURE 5 ABOUT HERE *****

3.1 Correlational analysis

The associations between age and COP metrics are shown in Figure 6. With the exception of the COP_{ML} amplitude during unipedal stance, there were statistically significant moderate to strong positive correlations between age across the adult life span (20 – 79 years) and all COP metrics (r= .43 to r = .71, $p<0.001$). When correlational analyses were performed only in the young and middle-aged groups (20 – 59 years), with the exception of COP_{ML} amplitude with the EC on a firm (p= 0.036, r = .33) and foam (p= 0.017, r= .37) surface, correlations coefficients were weak and not significant (Figure 6).

***** FIGURE 6 ABOUT HERE *****

The associations between age and SEBT/gait outcomes are shown in Figure 7. The analysis revealed statistically significant strong negative correlations between age across the adult life span (20 – 79 years) and all SEBT outcomes (r= .65 to .85, $p< 0.001$). When correlational analyses were performed only in the young and middle-aged groups (20 – 59 years), with the exception of the PL direction, again all correlations were statistically significant (Figure 7). However, the magnitude of the correlations were generally reduced (r= .41 to .77). Similarly, statistically significant moderate to strong correlations were observed between age across the adult life span (20 – 79 years) for comfortable and maximal gait velocity, and double limb support time (mean and variability) (r= .36 to .84). When correlational analyses were performed only in the young and middle-aged groups (20 – 59 years), statistically significant correlations were only observed for maximal gait velocity (r= .21) and the coefficient of variation of the double limb support time (r= .41) ($p< 0.05$) (Figure 7).

***** FIGURE 7 ABOUT HERE *****

4. DISCUSSION

In examining the ability of lower limb reaching performance, posturographic measures and gait metrics to differentiate between young, middle-aged and older adults, three unique findings were revealed: (i) deficits in lower extremity reach performance emerged in middle-aged adults and deteriorated appreciably in older adults, (ii) despite the introduction of several sensory and stance manipulations to render balance tasks more challenging, increased COP movement was only present among the oldest age group (60 – 79 years), (iii) however, correlational analyses revealed a graded increase in COP_{ML} amplitude and mean COP velocity when standing on a foam surface with the eyes closed throughout the adult lifespan, beginning in middle-age. These findings represent an original contribution to the existing literature and contribute to the early identification of potential balance deficits in those where balance problems do not yet exist, which will assist clinical decision making with respect to timely implementation of fall prevention strategies.

4.1 Age related changes in centre of pressure movement

The present findings are consistent with several existing literatures that have reported increased postural sway among older adults (Choy et al. 2003; Era et al. 2006; King et al. 2016; Roman-Liu, 2018). In a large cross-sectional study of 7,979 participants aged 30 years and over, Era et al. (2006) reported that differences in COP movement (bipedal, semi-tandem and tandem stance) were already present among young (30-39 years) and middle-aged (40-49 years) adults, with further accelerating declines in balance function after 60 years. In the present study, several manipulations were introduced to render balance task more challenging, such as reducing the size of the base of support (e.g. unipedal stance), decreasing visual (e.g. eye closure) and proprioceptive feedback (e.g. standing on a compliant surface) (King et al. 2016; Mancini and Horak, 2010; Visser et al. 2008). However, the between group analysis only revealed changes in postural stability among the older age group, compared to young and middle-aged adults. These findings are similar to previous studies that included only 20-30 adults in the middle-decades (Illing *et al.* 2010; Lord and Ward, 1994). It is likely that more participants would be required to identify earlier age-related changes in COP movements, particularly in the middle-decades.

An important extension to the current postural sway literature in the present study is that age was treated as a continuous variable using correlational analysis (in addition to dividing participants into distinct age categories as is traditionally done with analysis of variance) (Matson and Schinkel-Ivy, 2020; Riemann et al. 2018). The correlational analysis revealed two important novel findings. First, the strength of the association between age and COP movement was not altered by task difficulty or COP metric (amplitude and velocity). Second, whilst all COP measures (two exceptions) showed moderate to strong associations with age when the entire sample was included, all but two measures went from significant to non-significant when the age range was narrowed to exclude older adults. More specifically, we found moderate strength associations between the mean COP velocity and COP_{ML} amplitude when vision was removed and peripheral sensation and ankle support were reduced (eyes closed standing on foam), when the age range was restricted to young and middle-aged adults (20 – 59 years). Overall, these findings suggest that the relationship between age and these COP metrics are not driven exclusively by a rapid decline in balance in older adults, but instead point towards a graded increase in COP movements (reflecting an increase in postural sway) that was already present among middle-age adults. The decreased ability to balance on a compliant surface with the eyes closed (i.e. removed visual and proprioceptive sensory information) with advancing age supports the view that impairments may have already been present in the other sensory systems (vestibular and/or somatosensory) by middle-age (Choy et al. 2003). Given that performance in this test is associated with a history of previous falls (Anson et al. 2019), standing on foam with the eyes closed may yield more information with regards to screening for earlier age-related changes in postural balance. Moreover, mediolateral COP metrics can provide valuable information in predicting future falls and recurrent fallers (Piirtola and Era, 2006), while the mean COP velocity has been used to identify differences between elderly fallers and non-fallers (Howcroft et al. 2017). It is important to note there are some very specific scenarios where COP movements may actually be reduced in older adults. For example, when anxiety is experimentally induced (in which the environmental context is manipulated by elevating the standing surface), postural sway can actually decrease (Carpenter et al. 2006; Sturnieks et al. 2016). Such a reduction in the COP amplitude has been interpreted as an adaptive postural stiffening strategy in an attempt to "tighten" balance control to reduce the risk of the centre of mass exceeding the base of support. However, we do not believe this was the case in the current study, where such experimental manipulation was not involved. Our results would align with the general consensus in the literature (Choy et al. 2003; Era et al. 2006; King et al. 2016; Roman-Liu, 2018) that upright stance becomes less stable with older age, which manifests as an increase in the amplitude and velocity of the COP.

4.2 Age related changes in lower extremity reach performance

The SEBT is widely established as a valid test to identify lower extremity balance deficits (Gribble *et al.* 2012) and is associated with muscle strength/power (Booysen et al. 2015), and proprioception (Belley et al. 2016) in young adults. Existing studies have reported YBT performance (shared movement synergies with SEBT) in middle-aged (Bouillon and Baker, 2011; Freund et al. 2018) and older (Freund et al. 2018; Lee et al. 2015; Sipe et al. 2019) adults. Our study extends these findings in two important ways. First, the present study is the first to report SEBT performance across the adult life span. This is important because while the SEBT and YBT have shared movement synergies, reach values for the YBT are not transferable to SEBT performance (due different postural control strategies and test administration) (Coughlan et al. 2008). Second, in addition to determining balance differences between discrete age categories, age was also treated as a continuous variable through correlational analyses.

Between group analyses revealed that deficits in lower extremity reach performance emerged in middle-aged adults and deteriorated appreciably in older adults. The large magnitude differences in SEBT performance between young and middle-age groups (d= 0.71 – 1.74) highlight a substantial deterioration in balance performance by middle-age. Additionally, the moderate to strong inverse correlations between age and SEBT performance in the full sample (20 – 79 years) and when the analysis was confined to young and middle-age groups (20 – 59 years) suggests that age-related declines in lower extremity reach performance are continuous rather than abruptly occurring at a particular age. The present study highlights the potential importance of using lower extremity reaching tasks as a paradigm for determining age-related impairments in balance abilities that would not otherwise be detected during quiet standing tasks (Matson and Schinkel-Ivy, 2020). The earlier and more rapid decline in SEBT performance, than has been reported previously, could be explained by the greater physical demands of this task when compared to quiet standing tasks.

4.3 Age related changes in gait outcomes

Given that most falls occur during ambulatory tasks, such as walking or transfers (Talbot et al. 2005), spatial-temporal gait characteristics and ground reaction forces were used in the present study to characterise our sample. Comfortable and maximal gait speed (Bohannon, 1997) and double limb support time (mean and variability) (Hollman et al. 2011) in the present study were within normative age spectrums, confirming that our sample were healthy without any gait abnormalities. Consistent with the literature, our study revealed that maximum gait speed declined more steeply than comfortable gait speed with increasing age (Bohannon, 1997). This slower comfortable walking speed in older people was also accompanied by an increased time spent in double limb support, which aligns with previous findings (Lord et al. 1996; Cromwell and Newton, 2004; Laufer, 2005). It should be noted that there is a great deal of controversy concerning what factors of gait (i.e. walking speed or double support period) mostly affect stability during walking (Williams and Martin 2019) and that slower mobility and longer support times may not necessarily suggest that older people are more unstable. For example, the reduced walking speed and increased double limb support time could be an adaptive mechanism in an effort to improve gait stability among older adults (Sung, 2019). For these reasons, we also calculated gait variability, a marker of gait instability and fall-risk (Verghese et al. 2009). Crucially, we observed a considerable increase in the double limb support time variability among the oldest age group, compared to young and middle-age adults. This is important because fallers tend to demonstrate greater gait variability than non-fallers (Hausdorff et al. 2001) and double limb support time closely reflects balance control mechanisms (Gabell and Nayak, 1984).

4.5 Limitations

The present findings should be interpreted with the recognition that potential limitations exist. Despite the present study demonstrating that the SEBT could be a useful paradigm for determining age-related impairments in balance abilities that would not otherwise be detected during quiet standing tasks, there are limitations to using this assessment, owing to a lack of definitive published protocol for its administration. For example, given that reach distance is manually assessed, it can be difficult to accurately measure the farthest reach distance (Plisky et al. 2009). Additionally, there is great deal of controversy as to what criteria constitutes a successful reach (e.g. whether the reach foot is allowed to touch down). If touching down is allowed, it is difficult to quantify the amount of support gained from touching the floor. In contrast, if touchdown is not allowed, standardising the distance from the ground that the participant reach is also difficult. To overcome this, we asked participants to push a marker on the floor, in a similar way to the YBT. In addition, conducting the SEBT in its entirety, comprising 4 practice trials and 3 test trials in each of the 8 directions on each foot, with a total of 112 reach excursions, can prove time consuming and potentially even fatiguing. Another limitation was that our sample was relatively healthy and homogenous, which may restrict the generalisability of the study, although the samples homogeneity may have limited the influence of potential confounding factors. Subtle increases in postural sway (as deduced by an increase in COP movement) among middle-age adults would be more clearly ascertained through a larger and functionally diverse group. Finally, this is a cross-sectional study and therefore age-related differences in balance performance might not to reflect longitudinal changes over time.

5. CONCLUSION

The current study, for the first time, reports changes in the SEBT across the adult life span. We uniquely found that lower extremity reach performance reveals earlier age-related declines in postural stability that are not evident during quiet standing tasks of varying difficulty. However, some COP measures during the most challenging task (standing on foam with the eyes closed) showed that age-related changes in quiet standing balance are continuous, rather than abruptly occurring in old age. The complexity of balance makes it challenging to assess performance in a concise and holistic approach. However, we provide synthesis of various methods that differently stress the various subsets of our balance repertoire. This information will assist clinicians, physical therapists, researchers and practitioners to choose the most appropriate assessment for the purposes of identifying impairments, implementation of fall prevention interventions and evaluating change over time.

REFRENCES

Anson, E., Bigelow, R.T., Studenski, S., Deshpande, N., Agrawal, Y., 2019. Failure on the Foam Eyes Closed Test of Standing Balance Associated With Reduced Semicircular Canal Function in Healthy Older Adults. Ear Hear. https://doi.org/10.1097/AUD.0000000000000619

Belley, A.F., Bouffard, J., Brochu, K., Mercier, C., Roy, J.S., Bouyer, L., 2016. Development and reliability of a measure evaluating dynamic proprioception during walking with a robotized ankle-foot orthosis, and its relation to dynamic postural control. Gait Posture. https://doi.org/10.1016/j.gaitpost.2016.07.013

Bohannon, R.W., 1997. Comfortable and maximum walking speed of adults aged 20-79 years: Reference values and determinants. Age Ageing. https://doi.org/10.1093/ageing/26.1.15

Booysen, M.J., Gradidge, P.J.L., Watson, E., 2015. The relationships of eccentric strength and power with dynamic balance in male footballers. J. Sports Sci. https://doi.org/10.1080/02640414.2015.1064152

Bouillon, L.E., Baker, J.L., 2011. Dynamic balance differences as measured by the star excursion balance test between adult-aged and middle-aged women. Sports Health. https://doi.org/10.1177/1941738111414127

Carpenter, M. G., Adkin, A. L., Brawley, L. R., & Frank, J. S. (2006). Postural, physiological and psychological reactions to challenging balance: Does age make a difference? Age Ageing. DOI: 10.1093/ageing/afl002

Choy, N.L., Brauer, S., Nitz, J., 2003. Changes in Postural Stability in Women Aged 20 to 80 Years. Journals Gerontol. Ser. A Biol. Sci. Med. Sci. https://doi.org/10.1093/gerona/58.6.m525

Clifford, A.M., Holder-Powell, H., 2010. Postural control in healthy individuals. Clin. Biomech. https://doi.org/10.1016/j.clinbiomech.2010.03.005

Coughlan, G.F., Fullam, K., Delahunt, E., Gissane, C., Caulfield, B.M., 2012. A comparison between performance on selected directions of the star excursion balance test and the Y balance test. J. Athl. Train. https://doi.org/10.4085/1062-6050-47.4.03

Cromwell, R.L., Newton, R.A., 2004. Relationship between Balance and Gait Stability in Healthy Older Adults. J. Aging Phys. Act. https://doi.org/10.1123/japa.12.1.90

Donath, L., Kurz, E., Roth, R., Zahner, L., Faude, O., 2016. Leg and trunk muscle coordination and postural sway during increasingly difficult standing balance tasks in young and older adults. Maturitas. https://doi.org/10.1016/j.maturitas.2016.05.010

Era, P., Sainio, P., Koskinen, S., Haavisto, P., Vaara, M., Aromaa, A., 2006. Postural balance in a random sample of 7,979 subjects aged 30 years and over. Gerontology. https://doi.org/10.1159/000093652

Faul, F., Erdfelder, E., Lang, A.-G., Buchner, A., 2009. Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. Behav. Res. Methods.

Freund, J.E., Stetts, D.M., Oostindie, A., Shepherd, J., Vallabhajosula, S., 2019. Lower Quarter Y-Balance Test in healthy women 50–79 years old. J. Women Aging. https://doi.org/10.1080/08952841.2018.1510248

Gabell, A., Nayak, U.S.L., 1984. The effect of age on variability in gait. Journals Gerontol. https://doi.org/10.1093/geronj/39.6.662

Geurts, A.C.H., Nienhuis, B., Mulder, T.W., 1993. Intrasubject variability of selected force-platform parameters in the quantification of postural control. Arch. Phys. Med. Rehabil.

Gribble, P.A., Hertel, J., 2003. Considerations for normalizing measures of the Star Excursion Balance Test. Meas. Phys. Educ. Exerc. Sci. https://doi.org/10.1207/S15327841MPEE0702_3

Gribble, P.A., Hertel, J., Plisky, P., 2012. Using the star excursion balance test to assess dynamic postural-control deficits and outcomes in lower extremity injury: A literature and systematic review. J. Athl. Train. https://doi.org/10.4085/1062-6050-47.3.08

Hausdorff, J.M., Rios, D.A., Edelberg, H.K., 2001. Gait variability and fall risk in community-living older adults: A 1-year prospective study. Arch. Phys. Med. Rehabil. https://doi.org/10.1053/apmr.2001.24893

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. https://doi.org/10.3389/fphys.2018.01932

Hollman, J.H., McDade, E.M., Petersen, R.C., 2011. Normative spatiotemporal gait parameters in older adults. Gait Posture. https://doi.org/10.1016/j.gaitpost.2011.03.024

Hopkins, W.G., Marshall, S.W., Batterham, A.M., Hanin, J., 2009. Progressive statistics for studies in sports medicine and exercise science. Med. Sci. Sports Exerc. https://doi.org/10.1249/MSS.0b013e31818cb278

Howcroft, J., Lemaire, E.D., Kofman, J., McIlroy, W.E., 2017. Elderly fall risk prediction using static posturography. PLoS One. https://doi.org/10.1371/journal.pone.0172398

Illing, S., Choy, N.L., Nitz, J., Nolan, M., 2010. Sensory system function and postural stability in men aged 3080 years. Aging Male. https://doi.org/10.3109/13685531003657826

Isles, R.C., Low Choy, N.L., Steer, M., Nitz, J.C., 2004. Normal values of balance tests in women aged 20-80. J. Am. Geriatr. Soc. https://doi.org/10.1111/j.1532-5415.2004.52370.x

Johansson, J., Nordström, A., Gustafson, Y., Westling, G., Nordström, P., 2017. Increased postural sway during quiet stance as a risk factor for prospective falls in community-dwelling elderly individuals. Age Ageing. https://doi.org/10.1093/ageing/afx083

King, G. W., Abreu, E. L., Kelly, P. J., & Brotto, M. (2019). Neural control of postural sway: Relationship to strength measures in young and elderly adults. *Experimental Gerontology*. https://doi.org/10.1016/j.exger.2019.01.005

Laufer, Y., 2005. Effect of age on characteristics of forward and backward gait at preferred and accelerated walking speed. Journals Gerontol. - Ser. A Biol. Sci. Med. Sci. https://doi.org/10.1093/gerona/60.5.627

Lee, D.K., Kang, M.H., Lee, T.S., Oh, J.S., 2015. Relationships among the Y balance test, Berg Balance Scale, and lower limb strength in middle-aged and older females. Brazilian J. Phys. Ther. https://doi.org/10.1590/bjpt-rbf.2014.0096

Lord, S.R., Ward, J.A., 1994. Age-associated differences in sensori-motor function and balance in community dwelling women. Age Ageing. https://doi.org/10.1093/ageing/23.6.452

Lord, S.R., Ward, J.A., 1994. Age-associated differences in sensori-motor function and balance in community dwelling women. Age Ageing. https://doi.org/10.1093/ageing/23.6.452

Mancini, M., Horak, F.B., 2010. The relevance of clinical balance assessment tools to differentiate balance deficits. Eur. J. Phys. Rehabil. Med.

Matson, T., Schinkel-Ivy, A., 2020. How does balance during functional tasks change across older adulthood? Gait Posture. https://doi.org/10.1016/j.gaitpost.2019.09.020

Menant, J.C., Steele, J.R., Menz, H.B., Munro, B.J., Lord, S.R., 2009. Effects of walking surfaces and footwear on temporo-spatial gait parameters in young and older people. Gait Posture. https://doi.org/10.1016/j.gaitpost.2008.10.057

Norris, B., Trudelle-Jackson, E., 2011. Hip- and thigh-muscle activation during the star excursion balance test. J. Sport Rehabil. https://doi.org/10.1123/jsr.20.4.428

Objero, C.N., Wdowski, M.M., Hill, M.W., 2019. Can arm movements improve postural stability during challenging standing balance tasks? Gait Posture. https://doi.org/10.1016/j.gaitpost.2019.08.010

Paillard, T., Noé, F., 2015. Techniques and Methods for Testing the Postural Function in Healthy and Pathological Subjects. Biomed Res. Int. https://doi.org/10.1155/2015/891390

Pajala, S., Era, P., Koskenvuo, M., Kaprio, J., Törmäkangas, T., Rantanen, T., 2008. Force platform balance measures as predictors of indoor and outdoor falls in community-dwelling women aged 63-76 years. Journals Gerontol. - Ser. A Biol. Sci. Med. Sci. https://doi.org/10.1093/gerona/63.2.171

Piirtola, M., Era, P., 2006. Force platform measurements as predictors of falls among older people - A review. Gerontology. https://doi.org/10.1159/000089820

Pinsault, N., Vuillerme, N., 2009. Test-retest reliability of centre of foot pressure measures to assess postural control during unperturbed stance. Med. Eng. Phys. https://doi.org/10.1016/j.medengphy.2008.08.003

Plisky, P.J., Gorman, P.P., Butler, R.J., Kiesel, K.B., Underwood, F.B., Elkins, B., 2009. The reliability of an instrumented device for measuring components of the star excursion balance test. N. Am. J. Sports Phys. Ther.

Prince, F., Corriveau, H., Hebert, R., & Winter, D. A. (1997). Gait in the elderly. *Gait Posture* https://doi.org/10.1016/S0966-6362(97)01118-1

Riemann, B.L., Lininger, M., Kirkland, M.K., Petrizzo, J., 2018. Age related changes in balance performance during self-selected and narrow stance testing. Arch. Gerontol. Geriatr. https://doi.org/10.1016/j.archger.2017.11.012

Riis, J., Eika, F., Blomkvist, A.W., Rahbek, M.T., Eikhof, K.D., Hansen, M.D., Søndergaard, M., Ryg, J., Andersen, S., Jorgensen, M.G., 2020. Lifespan data on postural balance in multiple standing positions. Gait Posture. https://doi.org/10.1016/j.gaitpost.2019.11.004

Roman-Liu, D., 2018. Age-related changes in the range and velocity of postural sway. Arch. Gerontol. Geriatr. https://doi.org/10.1016/j.archger.2018.04.007

Rubenstein, L.Z., 2006. Falls in older people: Epidemiology, risk factors and strategies for prevention, in: Age and Ageing. https://doi.org/10.1093/ageing/afl084

Schoene, D., Wu, S.M.S., Mikolaizak, A.S., Menant, J.C., Smith, S.T., Delbaere, K., Lord, S.R., 2013. Discriminative ability and predictive validity of the timed up and go test in identifying older people who fall: Systematic review and meta-analysis. J. Am. Geriatr. Soc. https://doi.org/10.1111/jgs.12106

Sipe, C.L., Ramey, K.D., Plisky, P.P., Taylor, J.D., 2019. Y-balance test: A valid and reliable assessment in older adults. J. Aging Phys. Act. https://doi.org/10.1123/japa.2018-0330

Sturnieks, D. L., Delbaere, K., Brodie, M. A., & Lord, S. R. (2016). The influence of age, anxiety and concern about falling on postural sway when standing at an elevated level. Hum Mov Sci. doi: 10.1016/j.humov.2016.06.014

Sung, P.S., 2018. Increased double limb support times during walking in right limb dominant healthy older adults with low bone density. Gait Posture. https://doi.org/10.1016/j.gaitpost.2018.04.036

Talbot, L.A., Musiol, R.J., Witham, E.K., Metter, E.J., 2005. Falls in young, middle-aged and older community dwelling adults: Perceived cause, environmental factors and injury. BMC Public Health. https://doi.org/10.1186/1471-2458-5-86

Verghese, J., Holtzer, R., Lipton, R.B., Wang, C., 2009. Quantitative gait markers and incident fall risk in older adults. Journals Gerontol. - Ser. A Biol. Sci. Med. Sci. https://doi.org/10.1093/gerona/glp033

Visser, J.E., Carpenter, M.G., van der Kooij, H., Bloem, B.R., 2008. The clinical utility of posturography. Clin. Neurophysiol. https://doi.org/10.1016/j.clinph.2008.07.220

Williams, D.S., Martin, A.E., 2019. Gait modification when decreasing double support percentage. J. Biomech. https://doi.org/10.1016/j.jbiomech.2019.05.028

Figure 1. Box-and-whisker plots of COP measures when standing on a firm and foam surface with the eyes open and eyes closed across each age group. Each boxplot represents the median (centre line), 25th% (bottom of the box) and 75th% (top of the box) percentile, with the whiskers denoting minimum and maximum data points that are within the range. *Significantly different 60 – 79 years group (p < 0.001). **Significantly different 40 – 59 years group (p < 0.001) NB: COP_{ML}; amplitude of mediolateral centre of pressure displacement, COP_{AP}; amplitude of anteroposterior centre of pressure displacement; EO; eyes opens, EC; eyes closed

Figure 2. Box-and-whisker plots of COP measures when standing in a unipedal stance on the right and left limb across each age group. Each boxplot represents the median (centre line), 25th% (bottom of the box) and 75th% (top of the box) percentile, with the whiskers denoting minimum and maximum data points that are within the range. *Significantly different 60 – 79 years group (p < 0.001). NB: COP_{ML}; amplitude of mediolateral centre of pressure displacement, COP_{AP}; amplitude of anteroposterior centre of pressure displacement; EO; eyes opens, EC; eyes closed

Figure 3. Box-and-whisker plots of SEBT performance during right foot stance (left foot reach) across each age group. Each boxplot represents the median (centre line), 25th% (bottom of the box) and 75th% (top of the box) percentile, with the whiskers denoting minimum and maximum data points that are within the range. *Significantly different 60 – 79 years group (p < 0.001). **Significantly different 40 – 59 years group (p < 0.001). NB: ANT; anterior, AL; anterolateral, LAT; lateral, PL; posterolateral, POS; posterior, PM; posteromedial, MED; medial, AM; anteromedial

Figure 4. Box-and-whisker plots of SEBT performance during left foot stance (right foot reach) across each age group. Each boxplot represents the median (centre line), 25th% (bottom of the box) and 75th% (top of the box) percentile, with the whiskers denoting minimum and maximum data points that are within the range. *Significantly different 60 – 79 years group (p < 0.001). **Significantly different 40 – 59 years group (p < 0.001). NB: ANT; anterior, AL; anterolateral, LAT; lateral, PL; posterolateral, POS; posterior, PM; posteromedial, MED; medial, AM; anteromedial

Figure 5. Box-and-whisker plots of gait outcomes across each age group. Each boxplot represents the median (centre line), 25th% (bottom of the box) and 75th% (top of the box) percentile, with the whiskers denoting minimum and maximum data points that are within the range. *Significantly different 60 – 79 years group (p < 0.001). **Significantly different 40 – 59 years group (p < 0.001).

Figure 6. Pearson's *r* correlation coefficients between age and postural sway metrics for the entire sample (n = 60, 20 – 79 years) and only the young and middle-aged adults (n = 40, 20 – 59 years). *$p < 0.005$, **$p < 0.001$, ns = not significant $p > 0.05$. NB: COP_{ML}; amplitude of mediolateral centre of pressure displacement, COP_{AP}; amplitude of anteroposterior centre of pressure displacement; EO; eyes opens, EC; eyes closed

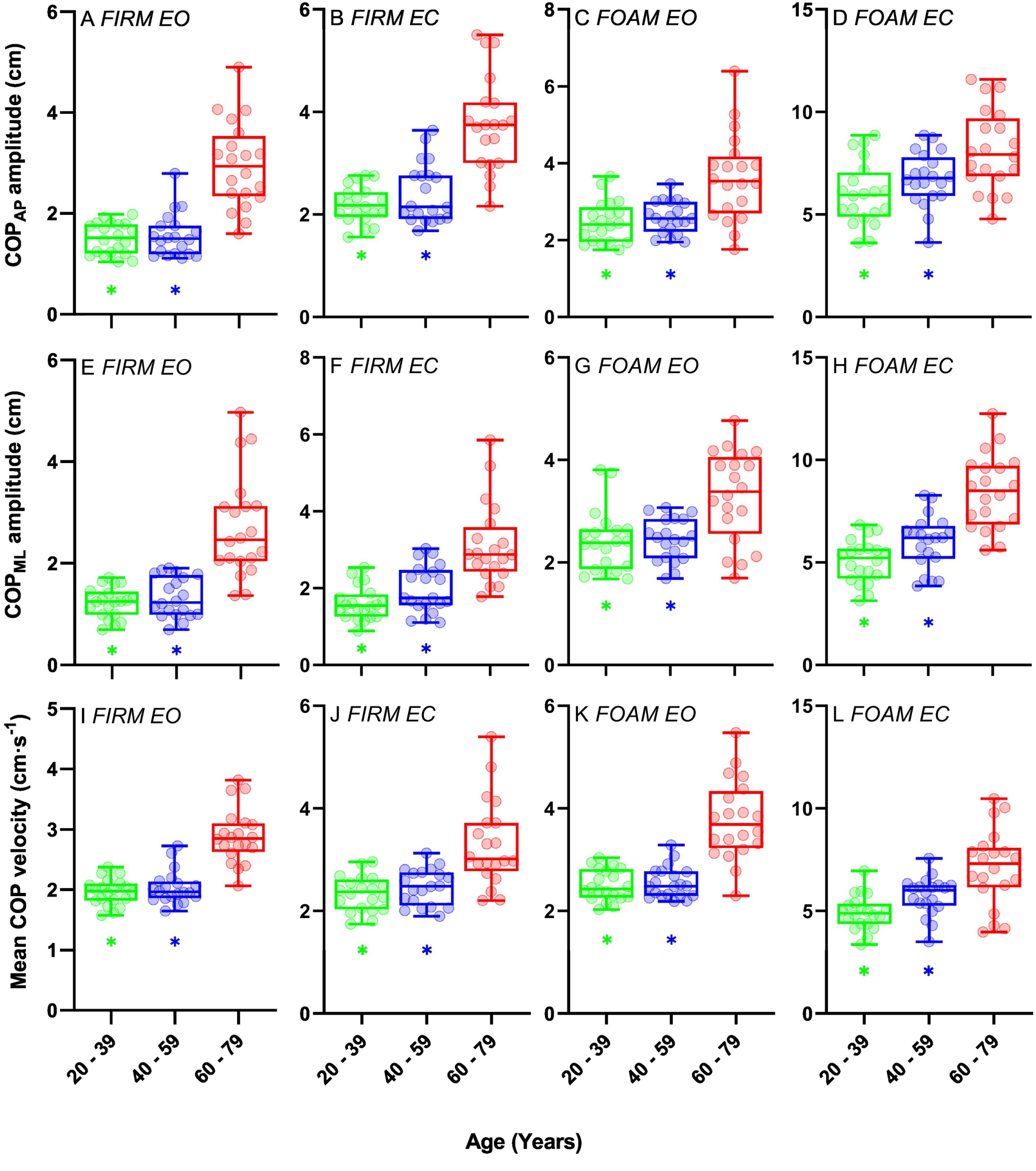
Figure 7. Pearson's *r* correlation coefficients between age and SEBT and gait metrics for the entire sample (n = 60, 20 – 79 years) and only the young and middle-aged adults (n = 40, 20 – 59 years). *$p < 0.005$, **$p < 0.001$, ns = not significant $p > 0.05$. NB: ANT; anterior, AL; anterolateral, LAT; lateral, PL; posterolateral, POS; posterior, PM; posteromedial, MED; medial, AM; anteromedial, CGV; comfortable gait velocity, MGV; maximal gait velocity, DLST; double limb support time

Author contributions

MH, MD and MP conceived and designed research. MH conducted experiments. MH performed the analyses and wrote the manuscript. MH, MD and MP, revised the manuscript. All authors read and approved the final manuscript.

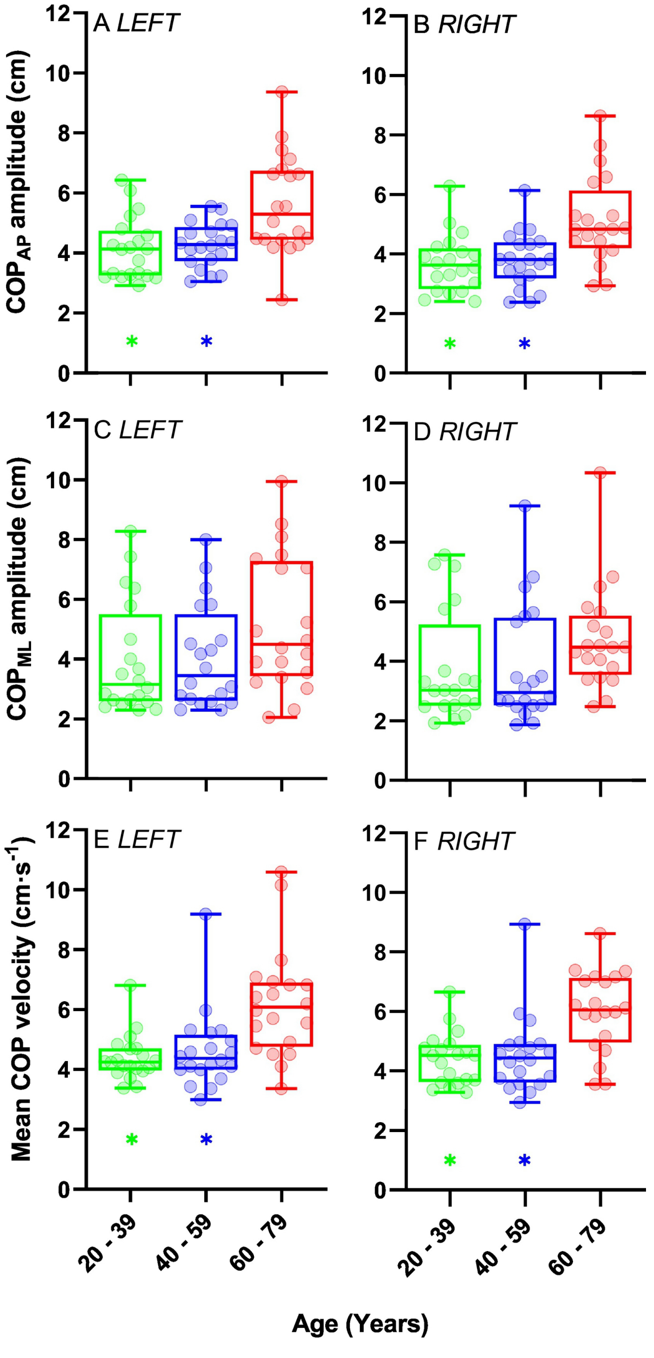
HIGHLIGHTS

- Increased centre of pressure movement was only present among the oldest age group
- Deficits in lower extremity reach performance emerged in middle-aged adults
- First study to report Star Excursion Balance Test across adult lifespan
- These findings will contribute to the early identification of balance deficits



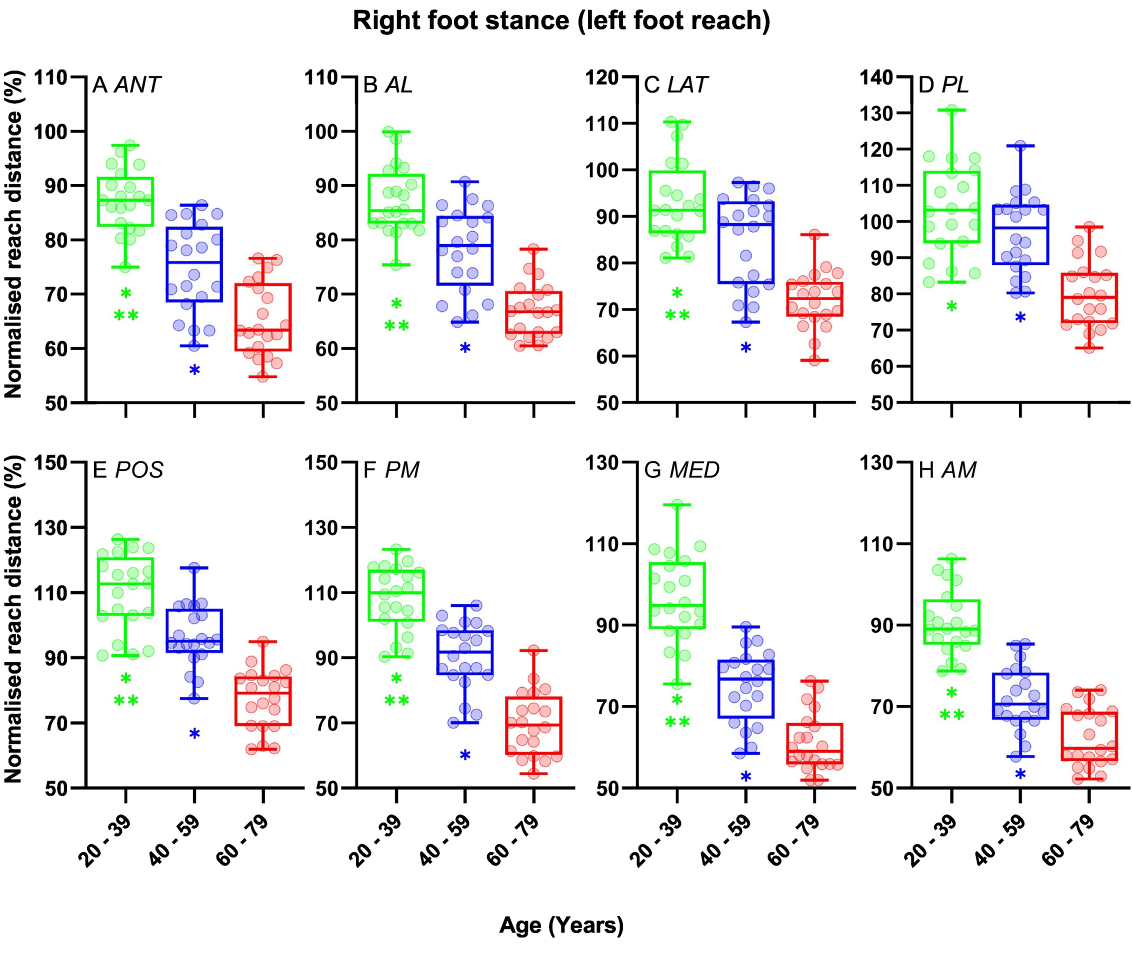
A FIRM EO
B FIRM EC
C FOAM EO
D FOAM EC
E FIRM EO
F FIRM EC
G FOAM EO
H FOAM EC
I FIRM EO
J FIRM EC
K FOAM EO
L FOAM EC
COPAP amplitude (cm)
COPML amplitude (cm)
Mean COP velocity (cm·s-1)
20 - 39
40 - 59
60 - 79
Age (Years)

Figure 1



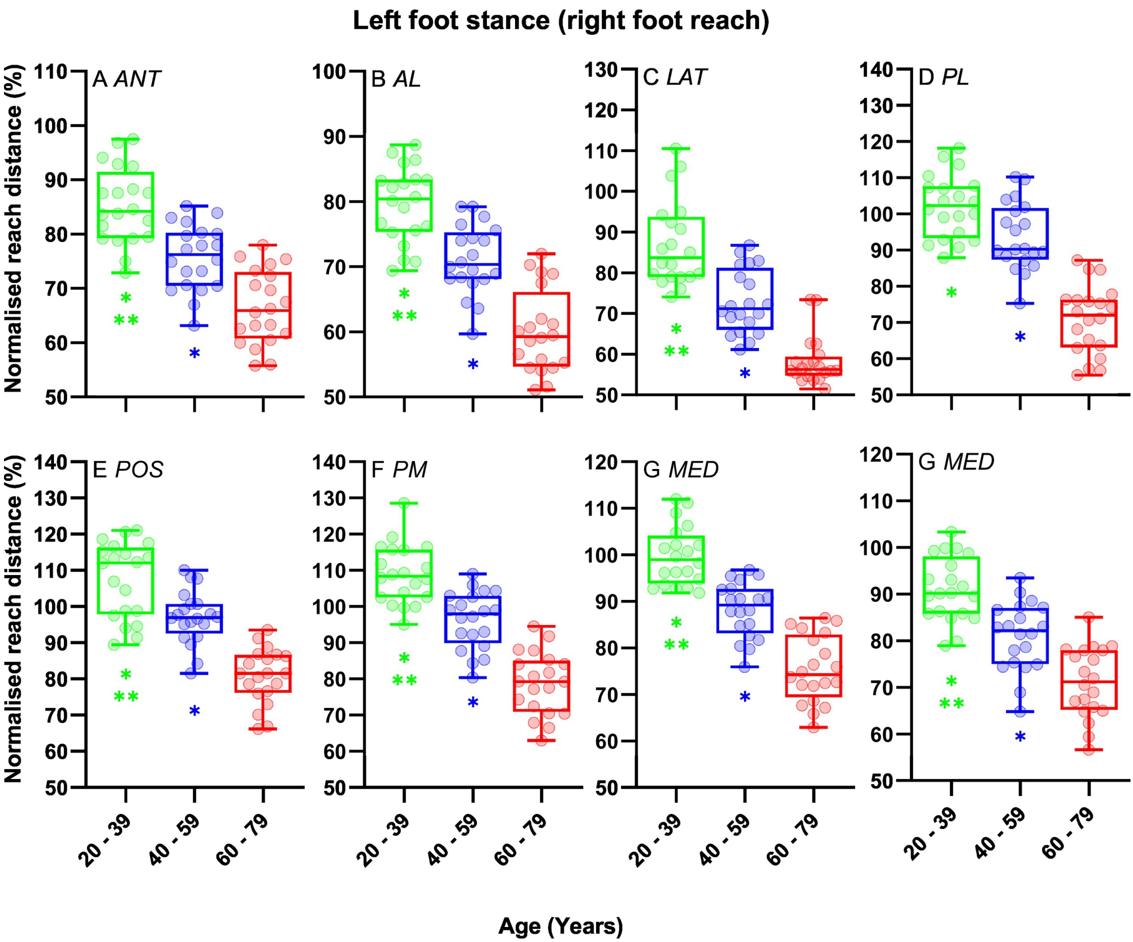
A LEFT
B RIGHT
C LEFT
D RIGHT
E LEFT
F RIGHT
COP$_{AP}$ amplitude (cm)
COP$_{ML}$ amplitude (cm)
Mean COP velocity (cm·s^{-1})
0
2
4
6
8
10
12
*
20 - 39
40 - 59
60 - 79
Age (Years)

Figure 2



Right foot stance (left foot reach)
A ANT
B AL
C LAT
D PL
E POS
F PM
G MED
H AM
Normalised reach distance (%)
20 - 39
40 - 59
60 - 79
Age (Years)

Figure 3



Left foot stance (right foot reach)
A ANT
B AL
C LAT
D PL
E POS
F PM
G MED
G MED
Normalised reach distance (%)
Normalised reach distance (%)
20 - 39
40 - 59
60 - 79
Age (Years)

Figure 4

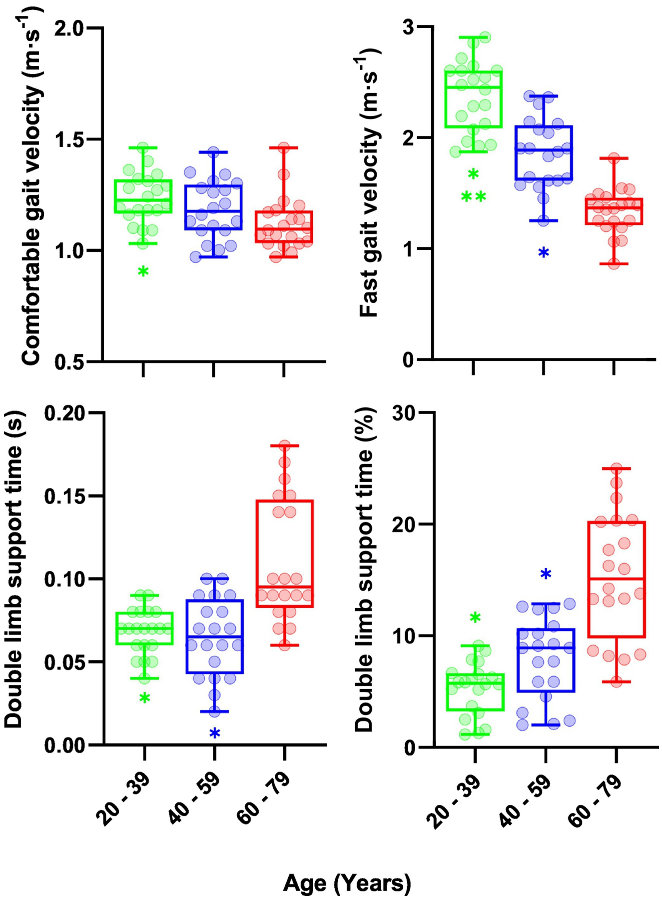
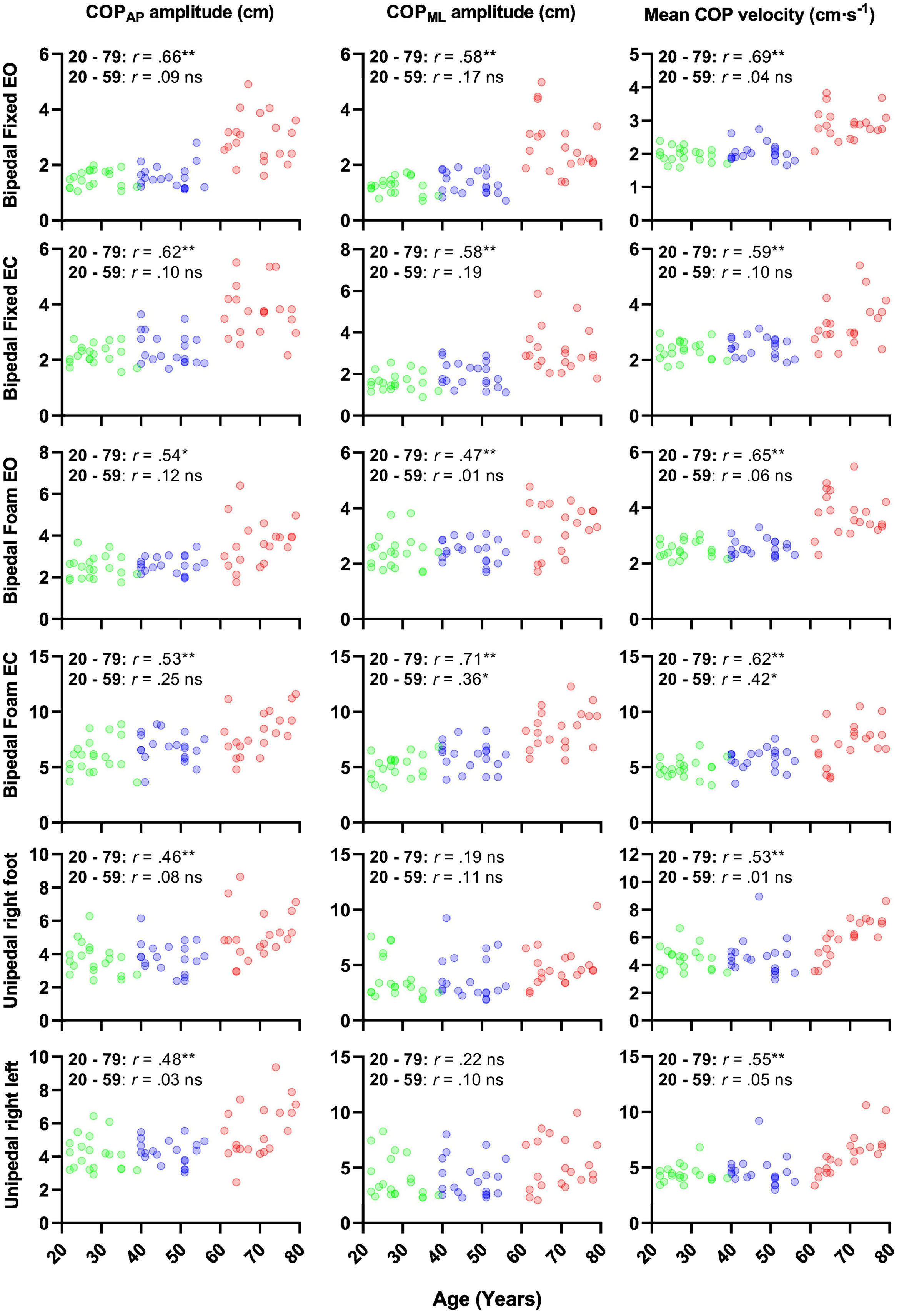
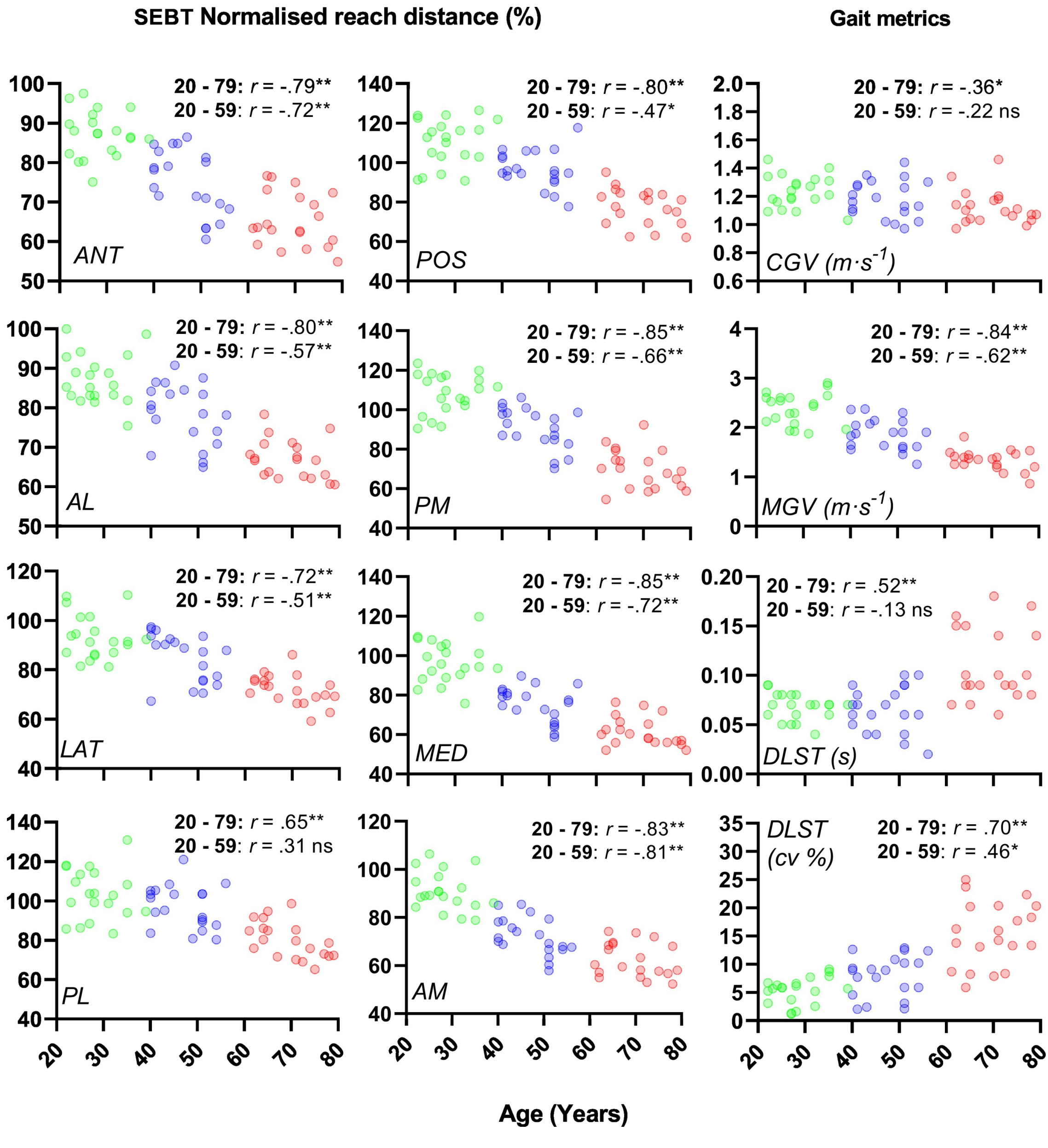

Comfortable gait velocity (m·s-1)
2.0
1.5
1.0
0.5
Fast gait velocity (m·s-1)
3
2
1
0
Double limb support time (s)
0.20
0.15
0.10
0.05
0.00
Double limb support time (%)
30
20
10
0
20 - 39
40 - 59
60 - 79
Age (Years)

Figure 5



COP_AP amplitude (cm)
COP_ML amplitude (cm)
Mean COP velocity (cm·s-1)
Bipedal Fixed EO
Bipedal Fixed EC
Bipedal Foam EO
Bipedal Foam EC
Unipedal right foot
Unipedal right left
20 - 79: r = .66**
20 - 59: r = .09 ns
20 - 79: r = .58**
20 - 59: r = .17 ns
20 - 79: r = .69**
20 - 59: r = .04 ns
20 - 79: r = .62**
20 - 59: r = .10 ns
20 - 79: r = .58**
20 - 59: r = .19
20 - 79: r = .59**
20 - 59: r = .10 ns
20 - 79: r = .54*
20 - 59: r = .12 ns
20 - 79: r = .47**
20 - 59: r = .01 ns
20 - 79: r = .65**
20 - 59: r = .06 ns
20 - 79: r = .53**
20 - 59: r = .25 ns
20 - 79: r = .71**
20 - 59: r = .36*
20 - 79: r = .62**
20 - 59: r = .42*
20 - 79: r = .46**
20 - 59: r = .08 ns
20 - 79: r = .19 ns
20 - 59: r = .11 ns
20 - 79: r = .53**
20 - 59: r = .01 ns
20 - 79: r = .48**
20 - 59: r = .03 ns
20 - 79: r = .22 ns
20 - 59: r = .10 ns
20 - 79: r = .55**
20 - 59: r = .05 ns
Age (Years)

Figure 6



SEBT Normalised reach distance (%)
Gait metrics
20 - 79: r = -.79**
20 - 59: r = -.72**
ANT
20 - 79: r = -.80**
20 - 59: r = -.47*
POS
20 - 79: r = -.36*
20 - 59: r = -.22 ns
CGV (m·s-1)
20 - 79: r = -.80**
20 - 59: r = -.57**
AL
20 - 79: r = -.85**
20 - 59: r = -.66**
PM
20 - 79: r = -.84**
20 - 59: r = -.62**
MGV (m·s-1)
20 - 79: r = -.72**
20 - 59: r = -.51**
LAT
20 - 79: r = -.85**
20 - 59: r = -.72**
MED
20 - 79: r = .52**
20 - 59: r = -.13 ns
DLST (s)
20 - 79: r = .65**
20 - 59: r = .31 ns
PL
20 - 79: r = -.83**
20 - 59: r = -.81**
AM
DLST (cv %)
20 - 79: r = .70**
20 - 59: r = .46*
Age (Years)

Figure 7