

Age-induced modifications in postural control and lower limb strength

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Abstract (192/250)

The postural sway during tasks of increasing difficulty and the isokinetic and isometric strength of knee extensors-flexors and ankle plantar flexors-dorsiflexors muscles were evaluated through ages. Sixty participants (27 women) were divided in 5 age groups (group 1: 21-30 years, group 2: 31-40 years, group 3: 41-50 years, group 4: 51-60 years and group 5: 61-75 years). They performed 3 static balance tasks with the eyes open and closed on a force plate: Normal Quiet Stance (30 s), Tandem Stance (20 s), and One Leg Stance (10 s). Posture was quantified using several Center of Pressure (CoP) variables in Anterior/Posterior and Medio/Lateral direction). They also performed maximal isokinetic and isometric knee extensions-flexions and plantar flexions-dorsiflexions. The CoP velocity increased gradually from group 1 to group 5. When narrowing the base of support, the CoP excursion increased for all age groups ($P < 0.05$). Knee and ankle muscles strength decreased gradually from group 1 to group 5. During all postural tasks, moderate (-0.39 to -0.61) correlations between CoP velocity and isometric strength of knee and ankle muscles were observed. Knee and ankle strength can be considered as predictors of static balance control, especially when postural requirements relate to narrower stance.

Keywords: Aging, Posture, Strength, Knee, Ankle

Introduction

Postural control plays an essential role in daily activities throughout lifespan. The maintenance of the upright stance is influenced by a combination of sensorimotor factors including visual acuity, peripheral sensation and lower-extremity muscle strength, all used to react to the constant changes in the environment (Lord et al., 1991). Recent investigations suggested that central nervous system employs individual control strategy to maintain body sway during a variety of task and postures. This strategy can be explained as a segment inverted pendulum control model, governed by torque developed at the most inferior joint accompanied by synergistic torques about superior joints (Blenkinsop et al., 2022). In particular, muscles acting around the ankle, knee and hip joint are of great relevance for maintaining posture (Amiridis et al., 2003; Kuo & Zajac, 1993). Moreover, dynapenia (poverty of strength) is often associated with reduced performance in daily living activities (Clark & Manini, 2008), decreased mobility, impaired standing balance (Amiridis et al., 2005), expanded hospitalization and less protection from falling in old age (Bijlsma et al., 2013).

Across different populations and conditions, postural control can be objectively evaluated in terms of postural performance and strategy by using reliable technological tools and tests (Paillard & Noé, 2015). Postural evaluation is often performed in bipedal standing. However, the introduction of more complex tasks, such as the tandem and the one leg stance, may provide a more comprehensive assessment of static balance (Šarabon et al., 2022). For example, Amiridis et al. (2003) reported an increase in postural sway as a result of narrowing the base of support in both young and old adults, with the old adults presenting greater displacement compared to young adults in each postural task. Accordingly, Cabral et al. (2020) have reported that posturographic assessment during a bipedal stance did not improve the prediction of recurrent and single fallers.

Aging results in physical and biological changes in the structure and function of musculoskeletal system that often leads to decline force production capacity and attributed as a potential underlying factor in the increasing prevalence of frailty, and the related mobility limitations in older adults (Perry et al., 2007). Interestingly, the age-related deterioration in strength is not uniform between lower extremity muscles as the rate of decline in plantar flexors force is the largest compared with other muscle groups (Danneskiold-Samsøe et al., 2009). A 4-time greater force reduction has been observed for the plantar flexors compared to dorsiflexors over a 12-year period longitudinal investigation (Winegard et al., 1996). Furthermore, Cattagni et al. (2014) have suggested that the assessment of ankle torque could be used as a measurement to discriminate elderly fallers from non-fallers. However, it has been reported that the strength of knee extensors is a potential predictor for mortality, functional limitation and physical disability in older people (Newman et al., 2006). Other studies

highlighted that age-induced deterioration in the neuromuscular performance concern both dorsiflexors and plantar flexors, as well as knee extensors and flexors muscles (Billot et al., 2010).

There is not a consensus in the literature regarding the relation between maximum strength of the lower limb and static balance control. While some studies have documented a significant association between postural control and plantar flexion and knee extension maximum isometric strength (Muehlbauer et al., 2015), others have failed to report similar results (Tavakkoli Oskouei et al., 2021). Moreover, Svoboda et al. (2019) indicated that the relation between muscle strength and postural control is age-dependent. These discrepancies between studies, may be influenced by the different characteristics of the observed population (age, gender and level of frailty) and may also be due to the different examination procedure that have been adopted by various studies to quantify postural control and muscle strength.

Relatively little is known about the age-induced modifications in postural control in tasks with increasing difficulty combined with muscle strength across the life span. The identification of individual with deteriorated balance control may have crucial implications for clinical practice, particularly in the assessment and management of balance-related issues. Additionally, this information may facilitate the design of tailored interventions aimed at improving postural control, reducing fall risk, and enhancing overall functional performance especially in elderly. Therefore, the aim of this study is to examine the postural control in tasks of increasing difficulty across different age groups, associated with the isometric strength of the major muscle groups of the lower limb.

Materials and Methods

A total of 60 adults (27 women) volunteered to participate in this study. They were divided into 5 age groups of 12 participants each (Group 1, 3 women, 21-30 years; mean age: 22.8 ± 2.5 years; height: 182.2 ± 11.9 cm; mass: 85.4 ± 13.1 kg; Group 2, 5 women, 31-40 years; mean age: 37.1 ± 3.1 years; height: 175.8 ± 12.3 cm; mass: 85.3 ± 16.5 kg; Group 3, 6 women, 41-50 years; mean age: 44.2 ± 2.1 years; height: 174.1 ± 9.4 cm; mass: 78.4 ± 10.8 kg; Group 4, 7 women, 51-60 years; mean age: 55.1 ± 2.3 years; height: 171.3 ± 9.5 cm; mass: 84.3 ± 12.1 kg; Group 5, 6 women, 61-75 years; mean age: 68.3 ± 4.7 years; height: 169.2 ± 7.8 cm; mass: 82.1 ± 10.5 kg). All participants were physically active, healthy and free from any neurological or musculoskeletal disease or impairment.

The exclusion criteria were neurological or vestibular diseases and surgery in lower limbs during the last 12 months. None of the older participants had suffered a fall during the 2 years preceding the study. The standardized Mini Mental Health Examination was used to confirm language competence and adequate cognition, with the requirement to score at least 25/30. All participants were firstly informed regarding the benefits and risks of the study and then provided written statements of informed consent. Approval (ERC-001/2020) for the experimental procedures was obtained from Aristotle University Ethics Committee on Human Research in accordance with the Declaration of Helsinki.

Postural control assessment

The static postural control was assessed on force platform type 9281CA (Kistler Instruments Ltd., Winterthur, Switzerland) at 1000 Hz. To evaluate static balance, three tasks of increasing difficulty in both eyes open (EO) and eyes closed (EC) conditions were used to explore balance dysfunction (Amiridis et al., 2003; Billot et al., 2010):

- I. Normal Quiet Stance (NQS). Participants were asked to stand barefoot on the platform in a comfortable position, with their feet parallel and the arms along the body for 60 s.
- II. Tandem Stance. Participants were asked to place the heel of the non-dominant foot in front of the toes of the dominant foot leaving no space between the feet with their arms on the hips for 20 s.
- III. One Leg Stance (OLS). The right foot was placed pointing straight forward in relation to reference lines in the frontal and sagittal planes for 10 s, while the left foot was raised above the ground with the hip flexed at about 45° (0° = hip angle at full standing position) and the knee at 45° (0° = full extension).

The participants were asked to stand barefoot on the platform in a comfortable position and were instructed to look straight ahead fixating their gaze at a marker (3-cm diameter) positioned at eye level at 1.5-m distance. They performed three trials on each balance task for both eyes open and closed in random order, for a total of 18 measurements. Between each trial, 1 min of rest was provided as needed. The best trial (less CoP displacement) was used for further analysis.

Signals were processed in MATLAB software (2020b) using custom-built scripts. Firstly, time series signals were filtered using a low-pass filter (Butterworth 4th order, 6 Hz). To quantify the postural stability, the following parameters were used: the average CoP velocity (CoP_{vel} , mm/s), the peak-to-peak amplitude (CoP_{max} , mm), the standard deviation (CoP_{sd} , mm) and the root mean square (CoP_{rms} , mm) of the CoP in anterior-posterior (A/P) and medio-lateral (M/L) axis (Figure 1).

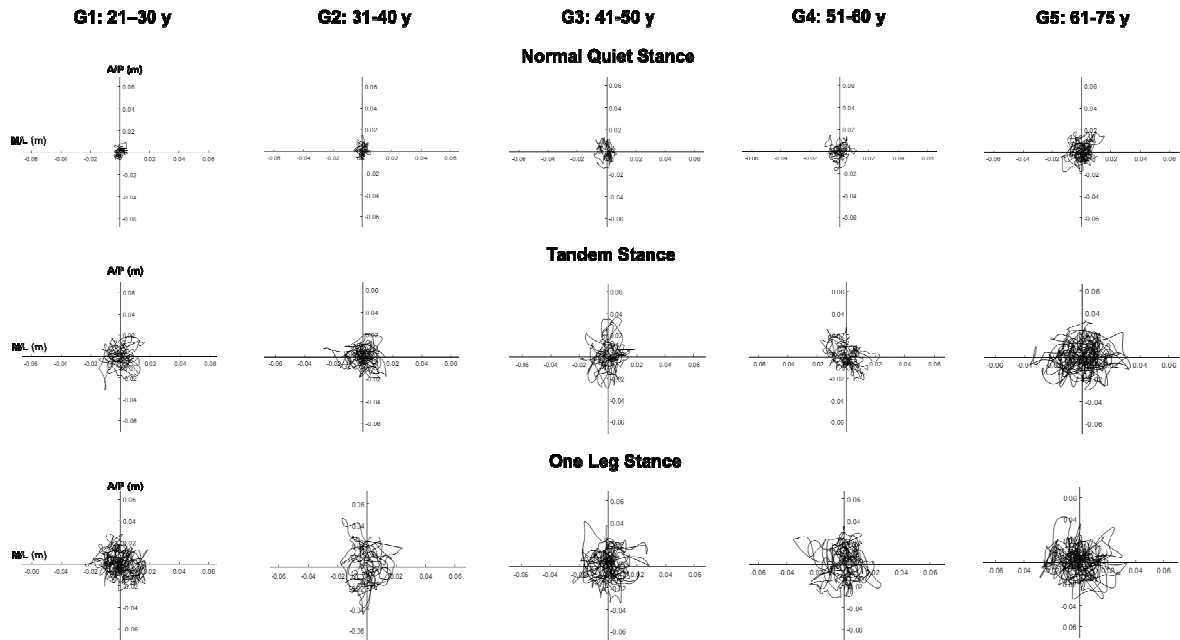


Figure 1: Representative recording of the center of pressure displacement across different age-groups (G1: 21-30 years, G2: 31-40 years, G3: 41-50 years, G4: 51-60 years, G5: 61-75 years) during normal quiet stance, tandem stance and one leg stance.

Muscle strength assessment

The peak torque (PT) of knee extensors (KE), knee flexors (KF), plantar flexors (PF) and dorsiflexors (DF) was measured by an isokinetic dynamometer (Cybex CSMI, Stoughton, MA, USA). The testing protocol of KE and KF consisted of 3 maximum contractions at 3 concentric ($60^{\circ}\cdot s^{-1}$, $120^{\circ}\cdot s^{-1}$ and $180^{\circ}\cdot s^{-1}$) and 2 eccentric ($60^{\circ}\cdot s^{-1}$ and $120^{\circ}\cdot s^{-1}$) velocities. In addition, 3 maximum isometric contractions were performed at 3 angular positions: 90° , 120° and 150° (180° = full knee extension). The dynamometer was adjusted to each subject, aligning the knee to the axis of rotation. During the examination, the participants were seated comfortably in the chair and securely fastened with hip, shoulder, and thigh using Velcro straps to prevent extraneous body movements.

Furthermore, the maximum PT of PF and DF was measured in a seated position with the knee fully extended during 3 concentric ($30^{\circ}\cdot s^{-1}$, $60^{\circ}\cdot s^{-1}$ and $120^{\circ}\cdot s^{-1}$) and 2 eccentric ($30^{\circ}\cdot s^{-1}$ and $60^{\circ}\cdot s^{-1}$) velocities. Also, the maximum isometric PF and DF torque was assessed at three ankle angles (75° , 90° and 105° , 180° = full ankle extension).

Calibration of the equipment was conducted according to the manufacturer's specifications before every assessment. Participants received standardized verbal instructions to exert the maximum strength possible and they had real time visual feedback of their torque output. All the tests were performed in a randomized order at the same time of the day to avoid any chronobiological effect. Prior to each test, the participants were instructed to perform 5-10 submaximal contractions to familiarize with the testing device. The effort which presented the greatest value was used for further analysis.

Statistical analysis

Data were analyzed using SPSS Statistics for Windows Version 27.0 (Version 27.0, IBM, Armonk, NY, USA). The Kolmogorov-Smirnov test was used to assess the normality of the data. Descriptive characteristics are presented as means and standard deviations. A three-way ($3 \times 2 \times 5$) analysis of variance (ANOVA) was applied to explore the differences between balance tasks (NQS, Tandem, OLS) at the different conditions (EO and EC) across the 5 age-groups. Further, to evaluate the differences in muscle strength between the groups, one-way ANOVA were used. Pearson's correlation coefficient was computed to explore the relationship between CoP velocity with the isometric muscle strength.

The joint angle at which the muscle group produced the greatest force was used for the correlation analysis. The isometric force at the knee angle of 120° was used for the maximum KE isometric torque and at 150° for the maximum KF isometric torque (Garcia et al., 2016). The respective optimal angles for the ankle muscles were 75° for the PF and 105° for the DF (Garcia et al., 2016). The strength of a correlation coefficient was interpreted as trivial (0-0.10), weak (0.10-0.39), moderate (0.40-0.69) and strong (0.70-0.99).

Results

Posture measurements

CoP Velocity

The three-way ANOVA for the CoP_{vel} revealed a task $\times$ vision $\times$ group interaction for both A/P ($F_{(8,110)} = 2.11$, $p < 0.05$, $\eta^2 = 0.13$) and M/L ($F_{(8,110)} = 40.83$, $p < 0.001$, $\eta^2 = 0.74$) directions. Post-hoc analysis showed significant differences between the balance tasks with the CoP_{vel} increased across them. Additionally, significant main effect of age was observed in both A/P ($F_{(4,55)} = 119.79$, $p < 0.001$, $\eta^2 = 0.89$) and M/L ($F_{(4,55)} = 99.91$, $p < 0.001$, $\eta^2 = 0.87$) axis with Group 3, 4 and 5 exhibited greater CoP_{vel} compared to Group 1 (Figure 2).

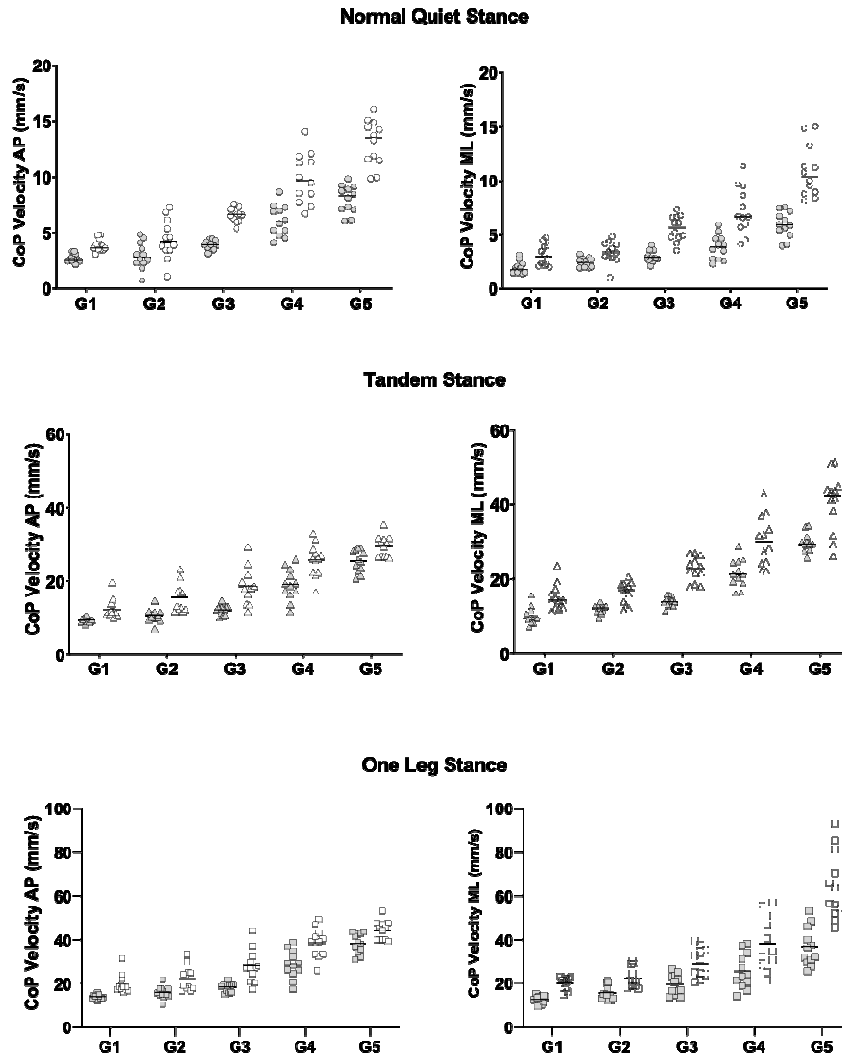


Figure 2: Scatter plot of the mean center of pressure (CoP) velocity at the anterior-posterior (AP) and medio-lateral (ML) direction across different age-groups (G1: 21-30 years, G2: 31-40 years, G3: 41-50 years, G4: 51-60 years, G5: 61-75 years) during normal quiet stance (circles), tandem stance (triangles) and one leg stance (squares) with the eyes open (filled) and eyes closed (open).

CoP SD

For the CoP_{sd} in the M/L ($F_{(8,110)} = 35.30$, $p < 0.001$, $\eta^2 = 0.72$), the ANOVA revealed a significant a task $\times$ vision $\times$ group interaction but not in the A/P ($F_{(2,110)} = 0.35$, $p > 0.05$, $\eta^2 = 0.02$) direction. Post-hoc analysis showed that CoP_{sd} was different between balance tasks with increasing difficulty. Further, significant effect of age was found in both A/P ($F_{(4,55)} = 59.51$, $p < 0.001$, $\eta^2 = 0.81$) and M/L ($F_{(4,55)} = 21.11$, $p < 0.001$, $\eta^2 = 0.60$) directions; the CoP_{sd} was lower in Group 1 compared to Group 3, 4 and 5 (Table 1).

CoP max

The three-way ANOVA for the CoP_{max} in the A/P ($F_{(8,110)} = 12.28$, $p < 0.001$, $\eta^2 = 0.47$) as well as in the M/L ($F_{(8,110)} = 29.84$, $p < 0.001$, $\eta^2 = 0.68$) direction indicated a significant task $\times$ vision $\times$ group interaction. The

post-hoc analysis exposed significant greater CoP_{max} as balance task difficulty increased. In addition, there was a significant main effect of age in A/P ($F_{(4,55)} = 274.63$, $p < 0.001$, $\eta^2 = 0.95$) and M/L ($F_{(4,55)} = 75.44$, $p < 0.001$, $\eta^2 = 0.84$) axis. The pairwise comparison showed that the Group 3, 4 and 5 presented higher values than the Group 1 in all the balance conditions (Table 1).

Table 1: Center of pressure variables during Normal Quiet Stance, Tandem Stance and One Leg Stance across the different age groups (n = 60).

	21-30 y	31-40 y	41-50 y	51-60 y	61-75 y
Normal Quiet Stance					
CoP Velocity A/P (mm/s)	2.6 ± 0.3	2.9 ± 1.1	3.9 ± 0.3	6.1 ± 1.3	8.1 ± 1.2
CoP Velocity M/L (mm/s)	1.9 ± 0.5	2.4 ± 0.4	2.9 ± 0.5	3.8 ± 1.1	5.9 ± 1.2
CoP SD A/P (mm)	0.6 ± 0.1	0.7 ± 0.2	1.1 ± 0.3	1.6 ± 0.4	2.3 ± 0.6
CoP SD ML (mm)	0.6 ± 0.1	0.7 ± 0.2	0.7 ± 0.1	0.8 ± 0.4	0.9 ± 0.3
CoP Max AP (mm)	2.1 ± 0.5	2.1 ± 0.6	2.9 ± 0.6	3.1 ± 0.9	4.6 ± 1.4
CoP Max ML (mm)	1.9 ± 0.3	2.7 ± 0.6	2.8 ± 0.6	2.9 ± 0.6	3.5 ± 0.4
CoP RMS AP (mm)	5.0 ± 1.8	5.8 ± 1.4	6.8 ± 1.7	7.9 ± 1.9	10.1 ± 1.4
CoP RMS ML (mm)	5.2 ± 1.6	5.2 ± 2.2	6.2 ± 2.4	7.6 ± 2.6	9.6 ± 2.5
Tandem Stance					
CoP Velocity AP (mm/s)	9.3 ± 0.6	10.5 ± 1.8	12.1 ± 1.3	19.1 ± 4.2	25.5 ± 3.1
CoP Velocity ML (mm/s)	10.1 ± 2.3	11.9 ± 1.1	13.9 ± 1.3	21.5 ± 3.7	29.7 ± 2.4
CoP SD AP (mm)	1.1 ± 0.4	1.2 ± 0.5	1.4 ± 0.5	2.2 ± 0.6	2.9 ± 0.9
CoP SD ML (mm)	1.4 ± 0.3	1.6 ± 0.4	1.8 ± 0.5	2.4 ± 0.3	2.9 ± 0.6
CoP Max AP (mm)	5.1 ± 1.1	5.6 ± 1.2	6.1 ± 1.3	10.2 ± 2.3	11.5 ± 2.9
CoP Max ML (mm)	5.1 ± 0.6	5.5 ± 0.5	7.2 ± 1.5	11.4 ± 2.4	12.3 ± 1.8
CoP RMS AP (mm)	8.9 ± 1.9	10.4 ± 1.7	12.4 ± 3.1	14.2 ± 3.7	17.1 ± 2.4
CoP RMS ML (mm)	8.7 ± 3.7	10.8 ± 2.8	13.1 ± 3.9	14.1 ± 3.6	17.4 ± 2.9
One Leg Stance					
CoP Velocity AP (mm/s)	13.9 ± 0.9	15.8 ± 2.7	18.2 ± 1.9	28.6 ± 6.3	38.2 ± 4.5
CoP Velocity ML (mm/s)	12.7 ± 1.8	15.6 ± 3.2	19.3 ± 4.5	25.5 ± 7.9	36.6 ± 8.7
CoP SD AP (mm)	1.4 ± 0.5	1.9 ± 0.7	2.4 ± 0.9	3.1 ± 1.1	3.8 ± 1.4
CoP SD ML (mm)	1.7 ± 0.2	2.3 ± 0.5	2.5 ± 0.6	2.9 ± 0.4	3.1 ± 1.2
CoP Max AP (mm)	8.7 ± 0.8	9.6 ± 0.9	10.6 ± 0.9	14.1 ± 1.6	18.5 ± 2.9
CoP Max ML (mm)	8.1 ± 0.9	9.7 ± 1.2	10.8 ± 2.9	15.5 ± 4.1	22.1 ± 5.9
CoP RMS AP (mm)	12.3 ± 4.3	13.7 ± 6.1	15.7 ± 9.3	18.8 ± 11.4	25.6 ± 7.3
CoP RMS ML (mm)	12.5 ± 3.7	14.4 ± 5.3	15.4 ± 4.4	17.2 ± 2.6	25.2 ± 16.7

CoP: Center of Pressure, SD: Standard Deviation, RMS: Root Mean Square, AP: Anterior-posterior, ML: Mediolateral

CoP RMS

The results of the three-way ANOVA for the CoP_{rms} exhibited no significant task x vision x groups interaction in A/P ($F_{(8,110)} = 0.30$, $p > 0.05$, $\eta^2 = 0.02$) and M/L direction ($F_{(8,110)} = 0.36$, $p > 0.05$, $\eta^2 = 0.02$). Although, there was a main effect of task on CoP_{rms} (A/P: $F_{(2,8)} = 77.95$, $p < 0.001$, $\eta^2 = 0.58$, M/L: $F_{(2,8)} = 73.96$, $p < 0.001$, $\eta^2 = 0.57$). Post hoc analysis showed that CoP_{rms} increased as difficulty of balance task increased. A significant effect of age was also observed (A/P: $F_{(4,55)} = 25.01$, $p < 0.001$, $\eta^2 = 0.64$, M/L: $F_{(4,55)} = 13.97$, $p < 0.001$, $\eta^2 = 0.5$) with the Group 1 presented lower CoP_{rms} values compared to Group 3, 4 and 5 (Table 1).

Strength measurements

Knee extensors strength

The ANOVA indicated significant differences for the PT of KE at all concentric velocities ($60^\circ \cdot s^{-1}$: $F_{(4,55)} = 6.10$, $p < 0.001$; $120^\circ \cdot s^{-1}$: $F_{(4,55)} = 7.04$, $p < 0.001$; $180^\circ \cdot s^{-1}$: $F_{(4,55)} = 5.69$, $p < 0.001$), with the Group 1 presented significant differences with the Group 3, 4 and 5 (Figure 3).

However, no significant differences were observed at the eccentric angular velocities (Figure 3). Moreover, significant differences were identified for the isometric PT of KE at all angular positions of the knee (90° : $F_{(4,55)} = 9.01$, $p < 0.001$; 120° : $F_{(4,55)} = 5.37$, $p < 0.001$; 150° : $F_{(4,55)} = 7.05$, $p < 0.001$) (Table 2).

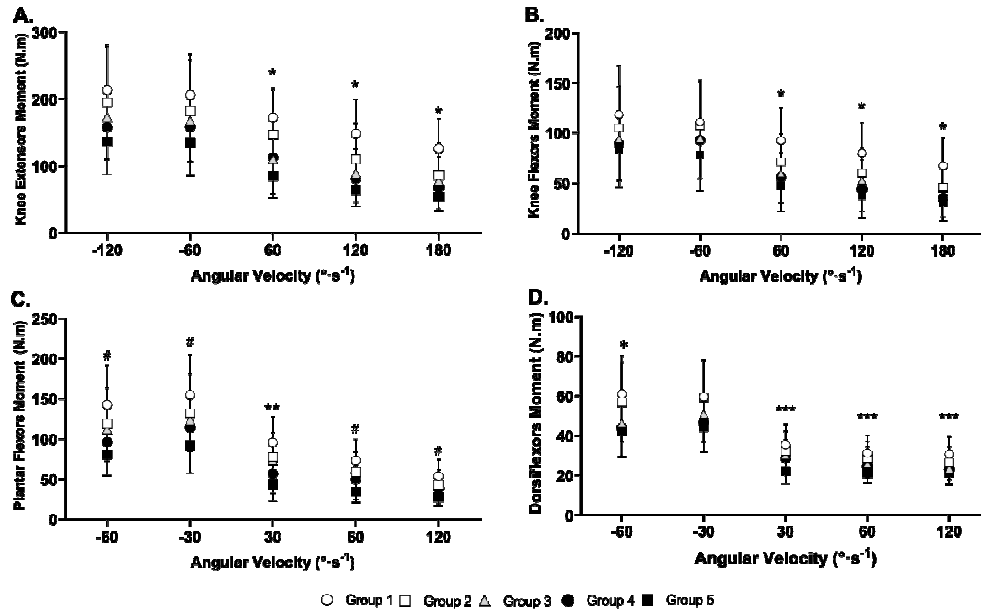


Figure 3: Mean and standard deviation of moment – angular velocity relationship of the four muscle groups (A: knee extensors, B: knee flexors, C: plantar flexors and D: dorsiflexors) across different age-groups (Group 1: 21-30 years, Group 2: 31-40 years, Group 3: 41-50 years, Group 4: 51-60 years, Group 5: 61-75 years). *: significant differences Group 1 (circle) vs Group 3 (grey triangle), 4 (filled circle) and 5 (filled square); #: significant differences Group 1 (circle) vs Group 5 (filled square); **: significant differences Group 1 (circle) vs Group 4 (filled circle) and 5 (filled square); ***: significant differences Group 1 (circle) vs Group 3 (grey triangle) and 5 (filled square).

Knee flexors strength

The ANOVA revealed significant differences in PT of KF at all concentric velocities ($60^{\circ}\cdot s^{-1}$: $F_{(4,55)} = 7.38$, $p < 0.001$; $120^{\circ}\cdot s^{-1}$: $F_{(4,55)} = 8.68$, $p < 0.001$; $180^{\circ}\cdot s^{-1}$: $F_{(4,55)} = 7.84$, $p < 0.001$) with the Group 1 presented significant differences with the Group 3, 4 and 5 (Figure 3). Significant differences were only identified for the PT of the KF at the eccentric velocity of $120^{\circ}\cdot s^{-1}$ ($F_{(4,55)} = 2.64$, $p < 0.05$) (Figure 3). Additionally, significant differences were also found for the isometric PT at all angular positions of the knee (90° : $F_{(4,55)} = 5.98$, $p < 0.001$; 120° : $F_{(4,55)} = 4.21$, $p < 0.01$; 150° : $F_{(4,55)} = 3.50$, $p < 0.05$) (Table 2).

Plantar flexors strength

Significant differences were presented for the PT of PF at all concentric velocities ($30^{\circ}\cdot s^{-1}$: $F_{(4,55)} = 6.06$, $p < 0.001$; $60^{\circ}\cdot s^{-1}$: $F_{(4,55)} = 4.29$, $p < 0.01$; $120^{\circ}\cdot s^{-1}$: $F_{(4,55)} = 4.19$, $p < 0.01$) with the Group 1 had greater strength compared with Group 5 at $60^{\circ}\cdot s^{-1}$ and $120^{\circ}\cdot s^{-1}$ and with the Group 4 and 5 at $30^{\circ}\cdot s^{-1}$ (Figure 3). The PT of PF were also different at both eccentric velocities ($30^{\circ}\cdot s^{-1}$: $F_{(4,55)} = 3.39$, $p < 0.05$; $60^{\circ}\cdot s^{-1}$: $F_{(4,55)} = 4.71$, $p < 0.01$) with the Group 1 produced more force compared to Group 5 (Figure 3). Further, the isometric PT was different between groups at all angular positions of the ankle (75° : $F_{(4,55)} = 9.05$, $p < 0.001$; 90° : $F_{(4,55)} = 7.81$, $p < 0.001$; 105° : $F_{(4,55)} = 5.81$, $p < 0.001$) (Table 2).

Dorsiflexors strength

Significant differences were observed for the PT of DF at all concentric velocities ($30^{\circ}\cdot s^{-1}$: $F_{(4,55)} = 5.31$, $p < 0.001$; $60^{\circ}\cdot s^{-1}$: $F_{(4,55)} = 5.02$, $p < 0.01$; $120^{\circ}\cdot s^{-1}$: $F_{(4,55)} = 4.19$, $p < 0.01$) with the Group 1 had greater strength compared with Group 3 and 5 (Figure 3). Moreover, significant differences for the PT of DF were identified only at the eccentric velocity of $60^{\circ}\cdot s^{-1}$ ($F_{(4,55)} = 3.09$, $p < 0.05$) (Figure 3). Finally, significant differences for the isometric PT of DF were found at the ankle angles of 75° ($F_{(4,55)} = 4.25$, $p < 0.01$) and 90° ($F_{(4,55)} = 4.13$, $p < 0.01$) among different groups (Table 2).

Correlation between isometric strength and center of pressure velocity

The correlation coefficients of CoP velocity with muscle strength are provided in Table 3. Pearson's test showed weak to moderate negative correlations between muscle strength and CoP velocity across the different balance conditions (the weaker the person, the greater the CoP velocity) (Figure 4). The respective r values ranged between -0.39 to -0.61.

Table 2: Mean and standard deviation of moment – angular position relationship of the four muscle groups.

		21-30 y	31-40 y	41-50 y	51-60 y	61-75 y
Knee						
90°	Extensors	230.2 ± 58.4*	179.7 ± 63.0	144.8 ± 43.3	133.9 ± 47.2	123.0 ± 33.5
	Flexors	107.2 ± 30.5*	88.7 ± 30.1	69.6 ± 23.1	74.9 ± 25.1	59.6 ± 20.7
120°	Extensors	232.4 ± 70.4*	196.6 ± 83.8	161.0 ± 47.5	142.2 ± 53.7	131.7 ± 46.1
	Flexors	121.0 ± 34.5*	110.3 ± 43.3	83.5 ± 31.8	84.0 ± 29.5	74.7 ± 25.7
150°	Extensors	172.8 ± 59.6*	135.1 ± 62.8	106.9 ± 38.2	94.7 ± 38.7	85.5 ± 15.0
	Flexors	129.8 ± 45.6*	113.4 ± 50.7	96.4 ± 32.5	90.8 ± 27.6	77.0 ± 27.5
Ankle						
75°	Plantar Flexors	190.7 ± 45.3*	162.4 ± 35.3	140.1 ± 36.0	126.8 ± 17.2	111.2 ± 39.3
	Dorsiflexors	19.8 ± 4.6*	17.8 ± 7.6	15.4 ± 6.1	13.6 ± 3.3	11.9 ± 3.8
90°	Plantar Flexors	147.6 ± 34.2*	121.6 ± 21.2	106.4 ± 31.2	95.8 ± 21.0	88.8 ± 34.1
	Dorsiflexors	32.2 ± 10.9*	31.8 ± 13.4	23.4 ± 8.5	22.5 ± 7.9	19.8 ± 6.3
105°	Plantar Flexors	88.6 ± 25.7*	79.7 ± 18.4	65.2 ± 12.4	64.0 ± 25.4	51.9 ± 18.2
	Dorsiflexors	45.0 ± 13.2*	43.8 ± 13.8	41.8 ± 11.9	36.6 ± 9.5	35.9 ± 11.4

*: significant differences between Group 1 compared to Group 3, 4 and 5 ($p < 0.05$).

Table 3: Correlation coefficient between Center of Pressure velocity during Normal Quiet Stance, Tandem Stance and One Leg Stance with eyes open (EO) and eyes closed (EC) and isometric muscle strength at optimal length for four muscular groups (n=60).

		Knee Extensors	Knee Flexors	Plantar Flexors	Dorsiflexors
Normal Quiet Stance					
EO	A/P	-.46**	-.42**	-.48**	-.57**
	M/L	-.51**	-.43**	-.49**	-.54**
EC	A/P	-.46**	-.44**	-.50**	-.58**
	M/L	-.48**	-.43**	-.51**	-.55**
Tandem Stance					
EO	A/P	-.46**	-.40**	-.49**	-.52**
	M/L	-.61**	-.58**	-.49**	-.57**
EC	A/P	-.46**	-.41**	-.58**	-.61**
	M/L	-.50**	-.44**	-.52**	-.59**
One Leg Stance					
EO	A/P	-.52**	-.42**	-.49**	-.52**
	M/L	-.50**	-.47**	-.43**	-.53**
EC	A/P	-.54**	-.52**	-.58**	-.61**
	M/L	-.46**	-.39**	-.43**	-.52**

NQS: Normal Quiet Stance, OLS: One Leg Stance, EO: Eyes Open, EC: Eyes Closed, A/P: Anterior/Posterior, M/L: Medio/Lateral. *: $p < 0.05$, **: $p < 0.01$.

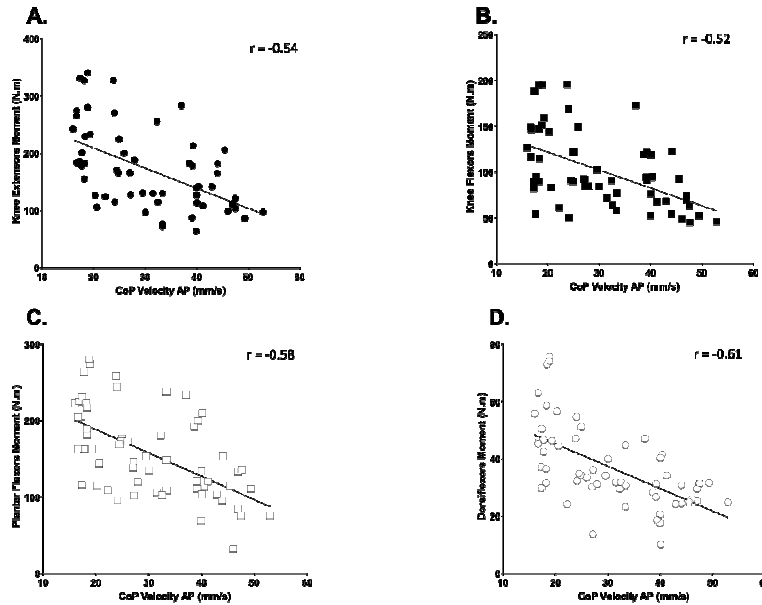


Figure 4: Scatter plots of the correlation (n = 60) between isometric strength at the optimal length for each muscle groups (A: knee extensors, B: knee flexors, C: plantar flexors and D: dorsiflexors) and mean center of pressure velocity (CoP_{vel}) at the anterior-posterior (AP) direction during the most demanding postural task (one leg stance).

Discussion

This study demonstrated that the decrease in postural control and muscle strength of the lower limbs is age-related, the CoP displacement increases with age and both knee and ankle muscles strength decrease. The negative correlation between CoP displacement and lower limb strength indicated that the weaker the person, the higher the postural sway, regardless of age. Moreover, the tasks of increasing difficulty and the absence of vision could be used across the ages to identify static balance deterioration.

Greater postural sway with age

Postural sway increased with increasing age (Figure 2 and Table 1). The differences between the age categories were more evident in more demanding balance tasks (tandem and OLS) compared to NQS. A linear decline of balance started from Group 3 (41-50 years), consistent with previous investigations (Amiridis et al., 2003; Era et al., 2006). In particular, Era et al. (2006) found that deterioration in postural control started at relatively young ages (> 40 years) and further accelerated after 60 years. Age-related changes in integration of sensory information from a wide range of sources (visual, vestibular and somatosensory) and the use of this information selectively to generate complex motor responses, appropriate in timing, direction and magnitude, could all potentially have impact on postural control (Maki & McIlroy, 1996). Our methodological approach cannot provide insights into the differential role of sensory systems, neural processing and conduction of information on balance performance, as we only removed the visual feedback. However, the absence of vision increases the reliance upon the nervous-system components, such as proprioception and vestibular function (Eikema et al., 2012). The deterioration of balance control in the elderly was associated with a mixed hip-ankle activation (Amiridis et al., 2003), related to insufficient torque production by ankle muscles requiring to counteract the greater moment of inertia in the A/P and M/L direction (Kuo & Zajac, 1993). Furthermore, a declining amount of physical activity, which has been observed in middle-aged and older adults, can be a confounding factor and may have harmful effects on the posture control mechanisms (Tudor-Locke et al., 2011). These degenerations of neural, muscular and skeletal mechanisms lead to increase susceptibility to falls, difficulties in activities of daily living and may predict poor survival (Lord et al., 1994).

Strength deterioration with age

Our results indicated that both isometric and concentric strength of lower limbs decreases with age, which is in agreement with previous investigations (Danneskiold-Samsøe et al., 2009). The reduction in strength is due to a combination of neural, muscular and tendinous factors, including the reduction of the recruitment and rate coding of motor units, the deterioration in the intrinsic force-generating capacity of muscle, the reduction in descending excitatory drive from supraspinal centers/cortical levels to the muscle (Manini & Clark, 2012), and the alterations in muscle architectural characteristics (Narici et al., 2003). Numerous studies have demonstrated reduction in muscle strength with aging, associated with a decrease in size and number of muscle fibers and in number of motoneurons. Interestingly, the difference in strength between the youngest (Group 1) and the oldest participants (Group 5) were not uniform for all types of contractions. Regardless of muscle groups, the mean difference between youngest and oldest participants in eccentric strength was 34%, whereas in isometric strength it was 50% and in maximal concentric strength 61%. A potential explanation for this observation is related to the mechanical and cellular origin of the mechanisms of the eccentric strength preservation in old adults. The age-induced accumulation of non-contractile material in the muscle-tendon unit of old adults could increase muscle stiffness and provide mechanical advantage during eccentric contractions (Roig et al., 2010). Klass et al. (2005) indicated that old adults presented a greater deficit during concentric and isometric actions compared to eccentric actions with the dorsiflexors. They attributed the smaller reductions in eccentric torque not to the difference in muscle activation or coactivation, but to alterations within the musculo-tendon complex. It is also reported that the slowing of cross-bridge cycling observed with advanced age may help minimize the loss of force during eccentric actions by increasing the force developed per cross-bridge (Larsson et al., 1997). Moreover, the increase in muscle collagen in the ageing muscle might enhance the number of attachments between tendon and sarcomeres that could contribute to an increase in passive torque during eccentric actions (Larsson et al., 1997).

Association between posture and strength

We have reported for the first-time results of postural tasks over a wide age spectrum along with a comprehensive assessment of muscle strength at the ankle and knee joint. Our results showed that isometric strength (measured at the optimal angle for each muscle group) was associated with the CoP_{vel} across balance tasks (the greater the force, the lower the CoP excursion). Even though maximal strength is not necessary to maintain postural stability during standing, our findings indicated significant association between posture and muscular strength. These results are in agreement with a recent systematic review that identified an association between isometric strength and static balance control (Muehlbauer et al., 2015). However, other studies reported only an association between isokinetic muscle strength and dynamic postural control, but no association between isometric strength was reported (Song et al., 2021). These discrepancies could be attributed to different types of contraction, postural tasks selection and variables to be evaluated. Providing insights into which factors can

influence postural control is essential for the identification and the improvement of balance disorders as they increase the risk of falling.

Balance deterioration with task difficulty

Regardless of age, an increase in CoP excursion with the increased difficulty of balance tasks (by narrowing the base of support) was observed (Amiridis et al., 2003, 2005; Billot et al., 2010; Era et al., 2006). Increasing postural demands for both young and older adults led to greater CoP displacements and muscular activity (Amiridis et al., 2003), as expected. Interestingly, the effect of visual feedback for middle-aged and older adults was specific to the task difficulty, as it was evident in more challenging postural tasks (see Figure 2). Postural assessment during an upright stance is considered a global balance test that can be easily employed to evaluate static balance control even if previous studies have reported controversial results (Amiridis et al., 2003; Era et al., 2006). It has been shown that older adults could present normal sway during NQS even though they have poor balance control and the relevance of the observed age-related differences within this task can be questionable (Šarabon et al., 2022). Thus, balance tasks with increasing difficulty, as selected in this study, are better to identify age-related differences. For example, the one leg stance is considered to be more suitable to better discriminate older adult fallers and non-fallers (Kozinc et al., 2020). Finally, the duration of each stance (30 sec for NQS, 20 sec for tandem stance and 10 sec for OLS) was adapted to the specific demands.

Limitations

This study was a cross-sectional investigation; prospective studies are needed to elucidate the long-term relation between the muscle strength and postural control. Also, we only evaluated the static and not the dynamic balance, which is considered more meaningful for the assessment of daily tasks.

In conclusion, middle-aged and older adults presented poorer postural control during balance tasks of increasing difficulty and lower limb strength compared to young adults. The postural control was correlated with the maximal strength of knee and ankle muscles.

Conclusion

Middle aged and older adults presented lower postural control during balance tasks of increasing difficulty and lower limb strength compared to young adults. The postural control was correlated with the maximal strength of knee and ankle muscles (the weaker the person, the greater the CoP displacement). It seems that knee and ankle strength may serve as valuable indicators of static balance control across life span. However, recent evidences highlighted that force steadiness during submaximal isometric contractions with the hip abductors and ankle dorsiflexors may have a significant role in the control of standing balance in healthy adults and should be considered in future studies (Davis et al., 2020).

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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