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Joint coordination in young and older adults during quiet stance: Effect of visual feedback of the center of pressure

Sandra Maria Sbeghen Ferreira Freitas [a,*], Marcos Duarte [b]

[a] Programa de Pós-Graduação em Fisioterapia, Universidade Cidade de São Paulo, Rua Cesário Galeno, 448/475 Tatuapé, São Paulo, SP 03071-000, Brazil
[b] Biomedical Engineering, Federal University of ABC, Santo André, SP, Brazil

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ABSTRACT

How aging affects body sway and joint coordination during quiet standing was investigated under two visual feedback conditions provided on a monitor screen: fixed and moving cursor representing the center of pressure (COP) position measured by a platform. The across-time joint motion variance of ankle, knee, hip, mid-trunk, and cervical spine leading to COP displacement was analyzed using the uncontrolled manifold approach. The body sway was assessed by the COP displacement. Young and older adults showed greater ankle joint contribution to COP displacement than the other joints. However, older adults showed larger variability of knee and mid-trunk joint motions than young adults. During the moving condition, the ankle joint contribution decreased and hip joint contribution increased for both groups, but the COP displacement increased only for the older adults. We conclude that joint coordination and body sway during quiet standing can be modified by providing COP visual feedback and that joint coordination is affected by aging.

1. Introduction

Postural sway is an inherent characteristic of the human behavior when individuals maintain an upright quiet posture. Typically, postural sway increases as individuals become older [1,2], and this fact has been used as a sign of alteration of the postural control system, which may contribute to the increase in the number of falls in older adults [3]. An increase in postural sway has also been linked to different patterns of joint coordination employed to maintain body posture. For example, it has been described that older adults rely more on their hips (called as "hip strategy") and young adults on their ankles (called as "ankle strategy") during quiet standing [1,4].

However, several other major joints are involved in posture stabilization during quiet standing and recent findings have pointed out that the ankle and hip strategies can be seen only as extreme coordination patterns of a continuum of possible solutions employed by the postural control system [5,6]. Hsu et al. [6] used the uncontrolled manifold (UCM) approach to partition the total joint motion variance related to the stabilization of the body's center of mass (COM) position during quiet standing by young adults in two components: one that does not affect the instantaneous COM position (variance within the UCM, V_{UCM}) and the other reflecting the fluctuations of COM position (variance orthogonal to the UCM, V_{ORT}). Overall, their findings indicated greater V_{UCM} compared to V_{ORT}, which suggest that flexible joint combinations are used to stabilize the COM position. Two open questions are whether elderly individuals also use flexible joint combinations, as observed in young adults, during quiet stance and whether any observed age-related difference in body sway is related to these selected patterns of joint coordination. Therefore, the first aim of this study was to investigate the patterns of joint coordination used by elderly and young individuals during quiet standing.

The use of real-time visual feedback of the center of pressure (COP) during a standing task is a common tool employed in evaluation and training of the postural control [7–11]. The influence of COP visual feedback on postural control of young and older adults during stance posture has been described before [7–10]. Dault et al. [8] observed that while young adults decreased the COP variability with COP visual feedback, older adults were not able to decrease it. This difference between groups was attributed to the fact that older adults were not able to adapt their control mechanisms needed to stabilize the COP position. In young adults, the positive effect of COP visual feedback has also been debated. Boudrahem and Rougier [9] observed that only 69% of the adults investigated in their study presented smaller COP displacement during standing with COP visual feedback than in the eyes-open condition. Duarte and Zatsiorsky [10] found that the use of COP visual feedback to reduce postural sway during quiet standing by

* Corresponding author. Tel.: +55 11 21781565.
E-mail address: smsf.freitas@gmail.com (S.M.S.F. Freitas).

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young adults is only effective at very low frequencies of sway, up to 0.05 Hz; and such low frequencies are related to the movement of the COG [12]. In this way, the COP visual feedback contribution would provide a reference position minimizing any slow postural drift. All these results could suggest the use of different patterns of joint coordination in order to stabilize the COP position when visual feedback of the COP is provided. Therefore, the second aim of this study was to investigate whether real-time COP visual feedback affects body sway and the selection of joint coordination patterns during quiet standing and whether such effect differs between the two age groups.

2. Methods

2.1. Participants

Ten young (four males, mean ± SD age, body mass, and height: 25 ± 4 yrs, 165 ± 9 cm, and 60 ± 10 kg) and ten older (five males, 65 ± 3 yrs, 165 ± 8 cm, 65 ± 13 kg) adults participated in the study. None of the subjects had any known postural or musculoskeletal disorders. Participants signed informed consent forms according to the procedures approved by the local ethics committee. The experimental procedure was conducted in accordance with the Declaration of Helsinki.

2.2. Experimental set-up and procedures

Participants stood barefoot in a comfortable position on a force platform (model OR6-WP-1000, AMTI, Watertown, MA) with their feet at shoulder width and hands crossed at the hip level. A custom code written in LabView 6.1 (National Instruments Corp.) was used to calculate and, simultaneously, show the current COP position on a computer monitor (real-time visual feedback). The center of the monitor (located 1 m in front of the participant) was aligned with the participant's eye height. The force plate data were sampled at 1000 Hz and the COP feedback was shown at 25 Hz.

Participants were asked to stand as still as possible in a comfortable posture for 45 s in two visual feedback conditions: fixed and moving cursor conditions. In the fixed condition, a fixed yellow dot on a black background was presented on the center of the screen. For the moving condition, the yellow dot represented the real-time COP position of the participant in the anterior-posterior direction. Postural sways in the anterior (posterior) direction resulted in upward (downward) movements of the yellow dot on the screen. In both conditions, the participants were asked to look at the yellow dot displayed on the screen and try to maintain their body as still as possible. For the moving condition, they were also asked to minimize the yellow dot movements. Fatigue was never reported by the participants.

Kinematics at the sagittal plane of the body segments were recorded during the tasks. Ten markers were placed on the right side of the participants' body at the spinous process of C7; directly anterior to the external auditory meatus; lateral aspect of the acromion process of the shoulder; lateral projection of the sixth thoracic vertebra; anterior iliac crest; greater femoral trochanter; lateral femoral epicondyle; lateral malleolus; calcaneus; and head of the fifth metatarsal. The markers position was recorded by a motion capture system (Proreflex240, Qualisys) at a sampling rate of 100 Hz.

2.3. Data analysis

The COP and the kinematic time-series were filtered with a fourth-order 10-Hz low-pass zero-lag Butterworth filter. The coordinates of the markers were used to compute five sagittal plane joint angles (degrees of freedom, DOF): cervical spine, mid-trunk, hip, knee, and ankle.

The UCM approach was performed to investigate how variations of the five joint motions affected the COP position. Although the COP displacement is affected by both displacement and acceleration of the joint angles; for quiet standing nearly identical results are obtained performing the UCM analysis based on the relation between joint angle displacement and center of mass or the COP displacement [13]. For this reason, a Jacobian [$J(\underline{\theta}_0)$] matrix was estimated by using a multiple linear regression analysis of the joint motions with the COP position [13]. Then, the mean free joint configuration was projected parallel and perpendicular into the null space of the partial derivative $J(\underline{\theta}_0)$. The variance within the UCM reflects the amount of joint angle variance that did not affect the average value of the selected performance variable, i.e., the COP location ("good variance" referred as V_{UCM}) and the variance orthogonal to the UCM reveals the amount of joint angle variance that changed the performance variable ("bad variance" referred as V_{ORT}). Significantly greater V_{UCM} than V_{ORT} indicates that flexible joint combinations were used without affecting the COP position. More details about the UCM-analysis method can be found elsewhere [14,15]. The joint angles and COP location time-series were divided into five equal parts for the analysis. The standard deviations of the COP and of the joint motion time-series were also computed within each period.

The hypothesis of stabilization of the COP location in the anterior–posterior direction has only one DOF and more joint motions are available to stabilize the COP than needed (5 − 1 = 4 DOF). Thus, the amount of V_{UCM} was normalized by 4, the number of DOF of the null space. Three hypothetical modes proposed by Hsu et al. [6] about the structure of V_{UCM} and V_{ORT} are presented in Fig. 1. Note that, for the same amount of joint variance, the structure of the variance components changed for each mode. It is hypothesized that the use of more joints could lead to increased amount of V_{UCM} and decreased amount of V_{ORT}. The contribution of each joint motion to the amount of V_{UCM} and V_{ORT} was also investigated. All dependent variables were averaged across time periods for statistical analysis.

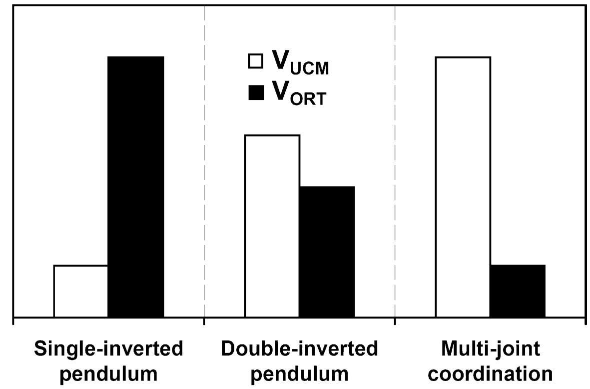

Fig. 1. Three hypothetical modes as proposed by Hsu et al. Each mode represents a different structure of V_{UCM} (joint configuration variance that does not affect the COP position) and V_{ORT} (joint configuration variance leading to COP variability) for the same amount of joint variance.

2.4. Statistical analysis

Mixed model analyses of variance (ANOVA) with one between-subject factor (group) and one (visual feedback conditions) or two (visual feedback conditions and component of variance) within-subject factors were performed on the COP standard deviation and joint variance, respectively. Three mixed model MANOVA with group by visual feedback conditions were ran on the dependent variables: standard deviation of joint angles and contribution of joint motion to V_{UCM} and V_{ORT}. Post hoc tests were carried out when necessary. The significance level was set at 0.05.

3. Results

Fig. 2 shows the standard deviation of COP time-series averaged across participants during fixed and moving conditions. ANOVA revealed statistically significant group *vs.* visual feedback interaction on the COP standard deviation ($F(1,18) = 5.8$; $p = 0.027$). Post hoc tests indicated that the older group presented larger COP standard deviation than the young group ($t[9] = -2.9$; $p = 0.018$) only in the moving condition. Post hoc tests also revealed a significant difference between the fixed and moving conditions for the older group ($t[9] = -2.8$; $p = 0.021$).

Fig. 3A shows the standard deviation of each joint angle for the young and older adults in both feedback conditions. MANOVA revealed only a significant main effect of feedback [Wilks' lambda = 0.47, $F(5,14) = 3.19$; $p = 0.04$]. Univariated analyses revealed effect of feedback only on the mid-trunk joint angle ($F(1,18) = 5.13$; $p = 0.036$). Approximately 25.1% (S.E. = 1.4%) of the total joint variability was due to the hip joint for the young group and 28.6% (S.E. = 1%) for the older group during the fixed feedback condition. This amount reduced to 21.1% (S.E. = 1.6%) and 25.2% (S.E. = 1.4%), respectively, for young and older groups during the moving feedback condition. ANOVA revealed significant main effects of feedback condition ($F(1,18) = 12.6$; $p = 0.002$) and group ($F(1,18) = 5.49$; $p = 0.03$), but no significant group *vs.* visual feedback interaction ($F(1,18) = 0.61$; $p = 0.81$), indicating that older adults used more hip joint motion than young adults as well as that the moving feedback condition reduces hip joint motion.

To investigate how much of the joint variability was related to the COP variability, the total joint variance was partitioned in V_{UCM} and V_{ORT} components (Fig. 3B). ANOVA revealed greater V_{UCM} compared to V_{ORT} ($F(1,18) = 84.66$; $p < 0.001$), indicating that, over

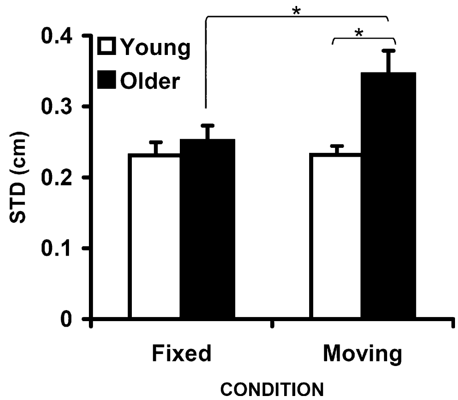

Fig. 2. COP standard deviation of young and older adults for the fixed and moving feedback conditions. Bars represent the averaged results across participants and error bar the standard error. *$p < 0.05$.

time, different patterns of joint combinations were used to maintain posture without affecting the COP location. The main effects of visual feedback ($F(1,18) = 1.65$; $p = 0.21$) and group ($F(1,18) = 1.55$; $p = 0.23$) were not revealed. However, ANOVA revealed a significant group *vs.* feedback interaction ($F(1,18) = 7.65$; $p = 0.01$) on the components of variance. Pairwise comparisons revealed that the two variance components of the older group were greater than the components of the young group only during the moving feedback condition ($t[9] > -2.33$; $p < 0.05$).

The contribution of each joint to the amount of V_{UCM} and V_{ORT} components of variance was also investigated (Fig. 3C and D, respectively). MANOVA revealed a main effect of feedback for the joint motion contribution to V_{UCM} ($F(5,14) = 6.41$; $p = 0.003$) as well as to V_{ORT} ($F(5,14) = 3.16$; $p = 0.04$). Overall, the contribution of ankle and hip joints to V_{UCM} increased and decreased, respectively, during moving condition (Fig. 3C) as indicated by the univariate tests ($F(1,18) = 10.76$; $p = 0.004$ and $F(1,18) = 13.53$; $p = 0.002$). On the other hand, for the contribution to V_{ORT} (Fig. 3D), univariate tests indicated that the contribution of the ankle joint decreased while the hip joint contribution increased during the moving condition ($F(1,18) = 11.33$; $p = 0.003$ and $F(1,18) = 7.13$; $p = 0.02$).

In addition, MANOVA revealed a group effect on the joints contribution to V_{UCM} ($F(5,14) = 4.40$; $p = 0.013$). However, univariate tests revealed that only the contribution of ankle joint was significant ($F(1,18) = 9.70$; $p = 0.006$). Such ankle joint contribution was greater for older adults than for young adults. For the contribution to V_{ORT}, MANOVA also showed a group effect on the contribution of joint motions to V_{ORT} ($F(5,14) = 5.82$; $p = 0.004$). Univariate tests indicated significant difference between groups for the contribution of ankle, knee, and mid-trunk joints. The contribution of the ankle was greater for the young adults than for the older adults ($F(1,18) = 9.61$; $p < 0.001$). On the other hand, the contribution of the knee and mid-trunk joints were greater for the older adults than for the young group ($F(1,18) = 7.05$; $p = 0.016$ and $F(1,18) = 18.35$; $p < 0.001$, respectively).

4. Discussion

The present results of the joint motion variability indicate that young and older adults used flexible joint configurations to stabilize the COP position during quiet standing. Overall, the amount of joint angle variability decreased in a top-down pattern, with the cervical spine joint being the most variable and the ankle

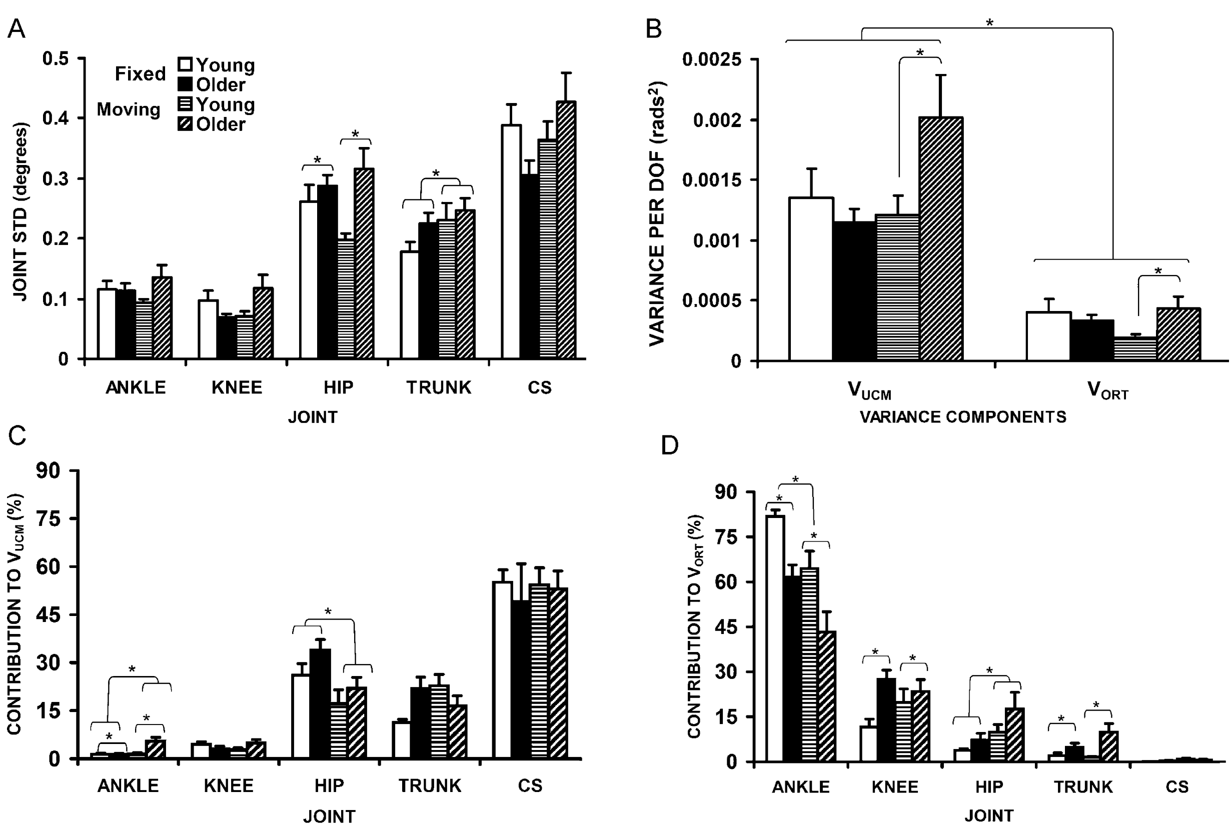

Fig. 3. (A) Standard deviation of joint motions (ankle, knee, hip, mid-trunk, and cervical spine), (B) components of variance (V_{UCM} and V_{ORT}), and contribution of each joint motion to the amount of (C) V_{UCM} and (D) V_{ORT} of young and older adults for fixed and moving feedback conditions. Bars represent the averaged results across participants and the error bars the standard error.

the least variable joint during quiet standing. However, anterior–posterior COP deviations were associated with a bottom-up pattern of the joint motion variability: the ankle joint contributed more while the cervical spine contributed least to the COP deviations. For the older group, the ankle joint also contributed less and the knee and mid-trunk joints variability contributed more to the COP deviations. The COP visual feedback also affected the joint contribution to V_{ORT}: all participants reduced the ankle joint contribution and increased the hip joint contribution during the moving feedback condition. However, the visual feedback affected differently the deviations of the COP position between groups. The older group increased the COP displacement while the young adults showed similar results between the fixed and moving visual feedback.

Our results from the young group corroborate with findings from previous studies that young adults use different combinations of joint angles leading to equivalent COM position while they constrain the use of joint angle combinations that lead to deviations of COM position during quiet standing [5,6]. The novel finding is that this strategy of selecting flexible joint combinations is also used by young and older adults independent of the visual feedback condition. This result is in according with the third hypothetical mode illustrated in Fig. 1. The fact that flexible joint configurations were used by both groups suggests that there is not merely one joint responsible for controlling the COP position and, consequently, maintaining body stabilization. It is possible that one joint has a greater effect on the COP position than others, but maintenance of the quiet standing seems to be accomplished by the covariation of several joint motions [5,6,16]. Indeed, large contributions of the ankle deviations to the COP displacement were observed for the young group, corroborating the classical idea that a postural strategy with more involvement of the ankle joint is used by young adults [1,17]. However, an important distinction is that at the present study we only quantified the variability of the joint movement and not its amplitude (or range of motion). For the older group, the ankle joint deviations also contributed most to COP displacement compared to the other joints. The contributions of the knee and mid-trunk joints deviations were also greater to the older group compared to young adults, suggesting that they use different joint combinations. In addition, for both conditions, more hip joint motion than ankle joint motion was responsible for the total joint variability. The use of a different coordination pattern by older adults during quiet standing could be associated with the insufficient torque production by ankle muscles due to aging [1] although such a hypothesis is not always supported during perturbation tasks [18]. Even though young adults rely, in general, most on their ankle joint motion, studies using unexpected external perturbations reported that they changed their patterns of joint coordination when the amplitude or speed of the perturbation increased [19]. The joint contribution to V_{ORT} observed in the present study, also suggested changes on the coordination patterns with the COP visual feedback. That is, the COP deviations were related to the increased contribution of the more proximal joints, in particular, the hip joint. Interestingly, they showed a reduction of the ankle joint contribution to the COP shifts in the moving feedback condition. The use of relatively more hip than ankle joint during the COP visual feedback condition is most probably related to the fact that a hip strategy typically presents a faster response that an ankle strategy because the moment of inertia of a double inverted pendulum (“hip strategy”) is smaller than of a single inverted pendulum (“ankle strategy”) [20].

Multi-joint synergies used to stabilize the instantaneous COM position have also been observed in more dynamic tasks such as whole-body voluntary movements during standing regardless of the information provided as visual feedback [16]. In that study, young adults used different joint combinations to perform the tasks, even though the provided visual feedback (represented as a cursor on the screen) was the instantaneous COP location or the excursion of one of the following joints: ankle, knee, or hip joint. Participants were also able to reduce the total joint motion when the task required oscillations of the cursor representing one of the visual feedback information between targets of small width and distance. In the current study, the modulation of the variability of joint motions was not explicitly required by the task. However, the young adults reduced them overall. On the other hand, older adults increased the hip and mid-trunk joints variability during the moving condition, which could lead to the increased COP deviations.

This visual feedback effect for older adults may be due to the fact that they are more influenced by the visual flow as reported by studies using a moving room paradigm [21,22] or COP visual feedback [8]. These studies showed that older adults have problems in integrating visual cues to produce appropriate motor action to stabilize body sway [8,21] and then, they were not able to reduce the COP variability with visual feedback, which was also attributed to a difficulty in using rotation around ankle joints. As consequence, it is possible that older adults use different patterns of joint coordination and have difficulties to efficiently change these patterns in order to reduce the COP deviations. These could be due to a sub-optimal postural control associated with their larger risk of falls [23]. However, new studies using a similar protocol but with more training sessions in elderly individuals should be necessary to investigate these questions. In addition, the present results can be applied only to the understanding of the anterior–posterior movements of the body segments and COP during standing. Although the same joints are involved in the control of posture at the frontal sagittal plane, when standing with the two feet in parallel there is a much higher demand for the hip mechanism and almost none for the ankle mechanism at the frontal plane [24].

An important clinical implication of the present findings is that although individuals may show an overall improvement in their postural control with the COP visual feedback rehabilitation, how this gain was achieved in terms of joint coordination strategies might be completely different from one subject to another. It might be necessary to look at the joint movement to better understand the individual adaptations.

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Conflict of interest

None declared.

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