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Research article

Older and young adults adopt different postural strategies during quiet bipedal stance after ankle plantarflexor fatigue

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ABSTRACT

Background: The individual effects of fatigue and age on postural control have been extensively studied. However, there is a lack of knowledge about the combined effects of fatigue and age on postural control and posture.
Research question: The purpose of this study was to investigate the influence of age and muscle fatigue on bipedal stance postural control and posture.
Methods: Twenty-three participants, fourteen young adults and nine older adults performed 30-s bipedal postural trials before and after fatigue. The fatigue protocol consisted in repeating heel raises until exhaustion. Back, hip, knee and ankle joint angles and centre of pressure (COP) displacements were recorded with a 3D motion capture system and a force plate.
Results: Fatigue induced similar increases in sway area and COP velocity for both populations. This was associated with a forward displacement of the COP position for both populations but with different postural adaptations. Similar increased flexions (+1.7 to 1.8°) for all joint angles (ankle, knee, hip and back) joints were observed after fatigue for older adults, whereas young adults mainly showed increased flexion for the ankle joint (+3.1°) and decreased flexion at the hip (−1.2°).
Significance: It can be argued that older adults act on all joints because they are too weak to sufficiently modify any joint individually, contrary to young adults. These posture adaptations may be strategies to cope with fatigue by limiting the reliance on fatigued plantarflexors, increasing ankle stiffness, increasing the sensitivity of muscle spindles, increasing the number of degrees of freedom of the task.

1. Introduction

Standing is most commonly and easily accomplished in a bipedal stance. This basic posture is assumed for much of the day and is the starting point for many other motor skills. The proprioceptive, visual, vestibular, and muscular systems interact to maintain this posture and limit the risks for falls that may be deleterious, especially for fragile individuals as the elderly [1]. Some conditions, such as fatigue and aging, impair balance and increase the risk for falls, emphasizing the need of a better understanding of the influence of these phenomena on posture and postural control.

The effect of muscle fatigue on standing postural control has been examined in numerous studies [2,3]. The key finding is that muscle fatigue increases centre of pressure (COP) sway area and velocities, both in young and older adults, which may increase the risk for falls [2,3]. In this context, calf muscles are typically targeted for fatigue as they play a major role in postural control during both unipedal and bipedal stances mainly by performing the required postural corrections in the antero-posterior plane [4–6]. This is explained by the fact that, during quiet standing, the projection of the centre of mass falls anterior to the axis of the talocrural joint. Consequently, fatigue of these muscle has been associated with alterations in postural control [7–9].

It has been inferred, from changes in COP, that fatigue may lead to postural adaptations, i.e., changes in joints angles [2]. This clearly

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demonstrates a need for kinematic information to fully understand the effects of fatigue on postural control. During quiet standing, movements used by an individual to maintain stability in the antero-posterior plane have been described as a hip strategy, an ankle strategy, or a combination of both [10,11]. The postural strategies used by an individual depend on numerous factors (e.g., support surface size, fear of falling). The ankle strategy is usually sufficient to maintain balance during "easy" postural tasks [12] (e.g., bipedal stance with vision), whereas the hip strategy is often used during more challenging tasks [4,13] (e.g., when vision is removed or when ground surface modified). Neuromuscular fatigue [14] is also one factor influencing the difficulty of the postural task. However, few studies have focused on the effect of fatigue on posture and postural strategies (i.e., joint angles and limb positions) measured kinematically [15–17]. We reported that the altered postural control during unipedal stance observed after fatigue of the ankle plantarflexor muscles was accompanied by an increase in ankle dorsiflexion angle [15,16]. Madigan et al. [17] reported that fatigue of the lumbar extensor muscles was accompanied by increased COP velocity standard deviations, increased joint angle variability and a greater ankle dorsiflexion during bipedal stance. These authors concluded that sway measured in terms of COP is not necessarily indicative of changes in joint kinematics justifying the use of both analyses simultaneously.

Another factor that may impact postural control is aging. It is known that aging negatively alters the neural and musculoskeletal systems [18] that are involved in balance. Moreover, several studies reported that older adults exhibit alterations in postural control for dynamic and static balance tasks compared with young adults [19–21]. However, the literature is relatively scarce about investigating the influence of the combination of fatigue and aging on postural control during quiet standing. A few studies have reported that postural sway observed after fatigue was greater in older adults compared to young adults [9,22]. The fact that these authors did not study kinematics makes it impossible to draw conclusions on the possible changes in angle joints associated with the reported alterations postural control. Nevertheless, the importance of understanding the influence of fatigue on balance in older adults is of interest considering the risk of falls of this population [23]. Only Papa et al. [24] looked at postural control and kinematics simultaneously, but their study was focused on reactive postural control during a fall test, and not on quiet standing.

The purpose of this study was to determine the effects of age and fatigue of the plantarflexor muscles on quiet bipedal postural control and postural adaptations. It was hypothesized that fatigue would induce increases in sway area and COP velocity for all participants, but with greater magnitude for older participants compared to younger ones. It was also hypothesized that joint angles would change, and more specifically, that an increased ankle flexion would be observed after fatigue.

2. Methods

Twenty-three healthy adults, 14 young (YA: 21.1 ± 3.1 years, 171.7 ± 10.6 cm, 65.4 ± 10.2 kg, 7 women and 7 men) and 9 older (OA: 73.4 ± 7.0 years; 164.1 ± 15.2 cm, 67.0 ± 22.7 kg, 5 women and 4 men) volunteered for the present study and gave their informed consent. There were no significant differences in height and weight between YA and OA ($p > 0.05$). YA and OA were recreationally physically active. The research protocol was approved by the ethics boards of the Bruyère Research Institute and of the University of Ottawa. None of the participants presented with any history of fall, injury, surgery, pathology of the lower limb or medication that could affect their ability to perform the experiment.

The experimental procedure is described below and illustrated in Fig. 1. During postural trials, subjects had to stand barefoot, feet together with their eyes open (EO) or closed (EC). We decided to include postural trials with eyes closed as vision removal increases the difficulty of the task which may promote differences between young and older

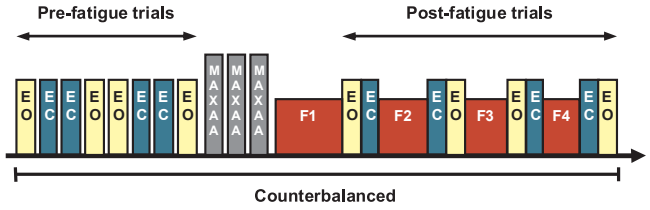


Fig. 1. Experimental procedure. EC: eyes closed, EO: eyes open, MAXAA: Maximal ankle angle testing. F1 to F4: fatigue protocols. 1 to 4.

adults. All postural trials lasted 30 s. Subjects started every trial with their hands at their sides and were instructed to sway as little as possible. The order of the postural trials was alternated and counterbalanced among subjects. First, subjects performed eight pre-fatigue (PRE) postural trials, four with EO and four with EC. Then, the maximal plantarflexion ankle angle was measured by requiring subjects to stand three times on the tip of their toes and to extend their ankle joints as much as possible. Afterwards, subjects performed the fatigue protocol which consisted of repeating ankle plantar flexions (bilateral heel raises) at a pace of 40 movements per minute. Participants were considered fatigued when they could no longer achieve 25% of their maximum ankle angle on three consecutive attempts. The real time feedback from the electronic goniometer was used to monitor the ankle angle of each repetition and accordingly determine the end of the test. Strong verbal encouragements were given throughout the fatigue protocol. Immediately after the fatigue protocol, subjects performed two post-fatigue (POST) trials, one with EO and one with EC. This sequence (i.e., one fatigue protocol and two post-fatigue trials) was repeated four times to obtain eight POST trials, four with EO and four with EC.

Considering the equipment, a force platform (Or6-6-1000, AMTI, USA) was used to record the displacements of the COP during postural trials (sampling frequency: 200 Hz, low-pass filter with cut-off frequency of 5 Hz). The platform was marked with tape, providing landmarks for subjects to ensure consistent positioning. A 6-camera motion capture system (Vicon Motion System Inc., USA) was used to assess the 3D position of body markers (sampling frequency: 200 Hz, low-pass filter with cut-off frequency of 5 Hz). Eighteen markers were placed bilaterally on subjects over the following landmarks: acromion process, lateral epicondyle of the humerus, proximal end of the third metacarpal, anterior superior iliac spine, greater trochanter, lateral epicondyle of the femur, lateral malleolus, distal end of the second metatarsal, and posterior calcaneus. An electronic goniometer (Biometrics Ltd., USA) attached to the foot and leg was used to allow online monitoring of the right ankle angle.

Considering the data analysis, we calculated five variables from the COP measures in order to assess postural control: the area of the 95% confidence ellipse (sway area, cm^2 [25]), the mean COP velocities in the medio-lateral (ML velocity, $cm\,s^{-1}$) and antero-posterior (AP velocity, $cm\,s^{-1}$) directions, and the mean position of the COP in the medio-lateral (ML position, cm) and antero-posterior directions (AP position, cm).

Body segments kinematics were extracted using 5 body segments created thank to the body markers as follow: foot (posterior calcaneus to lateral malleolus), leg (lateral malleolus to lateral epicondyle of the femur), thigh (lateral epincondyle of the femur to greater trochanter of the femur), pelvis (greater trochanter of the femur to anterior superior iliac spine), and trunk (anterior superior iliac spine to acromion process). These segments were used to calculate joint angles in the antero-posterior direction of the ankle (foot/leg), knee (leg/thigh), hip (thigh/pelvis), and back (pelvis/trunk). A neutral (0°) joint angle corresponded to a straight angle formed by two segments, except for the ankle where the neutral position was the standard anatomical position (right angle). Joint angles from both sides were averaged and expressed in degrees of flexion from the neutral position. For more details see [16]. Changes in aforementioned joint angles were used to assess changes in posture and

Table 1
Durations of the four fatigue protocols (FP). YA: young adults, OA: older adults. Data are presented as mean ± SD.

	1st FP[a]	2nd FP[a]	3rd FP[a]	4th FP[a]
YA	452.9 ± 84.0 s	314.5 ± 81.3 s	267.2 ± 77.8 s	239.0 ± 76.9 s
OA	166.8 ± 37.7 s	121.4 ± 46.6 s	110.2 ± 25.8 s	98.9 ± 26.5 s

[a] Significant statistical difference between YA and OA ($p < 0.001$).

postural adaptations. All computations concerning body markers were performed with Matlab 7 R14, 2005 (Mathworks, USA) and the open-source Biomechanical ToolKit package for Matlab.

Considering the statistical analysis, three-way mixed-model analyses of variance (ANOVA) were used to assess the effects of vision (EO, EC), age (YA, OA) and time (PRE, POST) on postural variables and joint angles. Two-way ANOVA for mixed models were used to assess the effect of age (YA, OA) and of repeating fatigue protocols (F1 to F4) on fatigue protocol durations. The level of significance was set at 0.05. When relevant, post-hoc tests were performed by means of Newman–Keuls procedures. Data are presented as mean ± SD.

3. Results

The duration of the fatigue protocols (Table 1) decreased with time for both populations ($p < 0.001$, $\eta_p^2 = 0.92$). YA performed each fatigue protocol longer ($p < 0.001$, $\eta_p^2 = 0.76$) than OA. No interaction was found.

Postural variables were altered by fatigue and vision but not by age (no main age effect or interaction). Sway area was 177% higher ($p < 0.001$) during POST (10.47 ± 4.28 cm^2) than during PRE (3.78 ± 1.57 cm^2) (main effect of time, $F(5,105) = 51.3$, $p < 0.001$, $\eta_p^2 = 0.71$). Sway area was 15% greater with EC (6.24 ± 3.53 cm^2) than with EO (5.41 ± 3.08 cm^2) (main effect of vision, $F(1,21) = 16.8$, $p < 0.001$, $\eta_p^2 = 0.44$). Similarly, the main effect of time ($F(5,105) = 16.9$, $p < 0.001$, $\eta_p^2 = 0.45$) indicated that ML velocity was 25% higher ($p < 0.001$) during POST (1.54 ± 0.42 cm s^{-1}) than during PRE (1.24 ± 0.30 cm s^{-1}). ML velocity was 19% higher with EC (1.45 ± 0.38 cm s^{-1}) than with EO (1.21 ± 0.26 cm s^{-1}) (main effect of vision, $F(1,21) = 47.9$, $p < 0.001$, $\eta_p^2 = 0.70$). Moreover, AP velocity was 40% higher ($p < 0.001$) during POST (1.74 ± 0.47 cm s^{-1}) than PRE (1.25 ± 0.22 cm s^{-1}) (main effect of time ($F(5, 105) = 27.2$, $p < 0.001$, $\eta^2p = 0.56$). AP velocity was 16% greater ($p < 0.001$) with EC (1.48 ± 0.37 cm s^{-1}) than with EO (1.28 ± 0.30 cm s^{-1}) (main effects of vision ($F(1, 21) = 61.7$, $p < 0.001$, $\eta^2p = 0.75$). Considering the ML position of the COP, no significant main effect or interaction was found. However, the AP position of the COP was 1.38 cm (36%) more forward during POST (−2.48 ± 2.14 cm, $p < 0.001$) than during PRE (−3.86 ± 2.12 cm) (main effect of time ($F(1, 21) = 13.7$, $p < 0.001$, $\eta^2p = 0.75$).

Different changes in joint angles were observed between young and older adults after fatigue (Table 2). While the ankle joint angles were similar between YA and OA during PRE ($p > 0.05$), a greater increase in flexion was observed for YA (+3.1°, $p < 0.001$) than for OA (+1.7°, $p < 0.01$) during POST (time × age interaction ($F(1, 21) = 5.0$, $p < 0.05$, $\eta_p^2 = 0.2$, observed power = 0.6). The knee joint angles were 2.2° more flexed during POST (10.4 ± 6.3°) than during PRE (8.2 ± 4.5°) (main effect of time ($F(1, 21) = 8.6$, $p < 0.01$, $\eta_p^2 = 0.3$, observed power = 0.8). As no age effect or interaction was found, this result refers to both groups. While a trend toward flexion reduction was observed for YA ($p = 0.07$), OA hip joints were 1.8° more flexed ($p < 0.01$) during POST (52.4 ± 10.3°) than PRE (50.6 ± 10.1°) (time × age interaction ($F(1, 21) = 4.8$, $p < 0.05$, $\eta_p^2 = 0.2$, observed power = 0.6). The back joint was 1.9° more flexed during POST (−63.7 ± 7.5°) than during PRE (−65.6 ± 7.1°) (main effect of time ($F(1, 21) = 15.6$, $p < 0.001$, $\eta_p^2 = 0.4$, observed power = 0.9). As no age effect or interaction was found, this result refers to both groups. Vision did not elicit any difference between groups.

4. Discussion

The purpose of this study was to determine the effects of age and fatigue on bipedal postural control and posture. Our major findings are that fatigue impaired postural control in young and older participants similarly. However, postural adaptations were different between the two groups. Young adults mainly altered the ankle joints to adapt to fatigue while older adults showed changes at all tested joints, i.e., the ankle, knee, hip and back joints.

4.1. Influence of vision, fatigue and age on postural variables

Postural variables were negatively affected when vision was removed which shows the importance of vision in postural control. Because this is well known [26] and that the presence or absence of vision did not influence the present results, we will not expand on this topic any further.

As expected, fatigue induced increases in sway area and ML and AP sway velocities, indicating impairment in postural control. This result was expected and in accordance with the literature [2]. However, we expected that fatigue would have a greater impact on the postural control of older adults as illustrated recently [9], but we observed no significant age effect. This may be explained by the fact that we recruited older adults that are still active and physically healthy. Another explanation could come from the performance of the fatigue protocols. Indeed, older adults performed all fatigue tasks for shorter duration than young adults. This could be due to limited physical capacities due to aging [18] or to differences in motivation, despite the strong encouragements that were provided during the fatigue tasks. The fear of falling usually observed in old adults could explain this strategy to minimize the extent of fatigue (self-preservation strategy) [27]. The use of a dynamometer and electrical stimulation to make sure that the level of fatigue is similar between participants would be needed to ensure that this is not a confounding factor. In the present study, the magnitude of the ankle joint angle and the ability to rise on heels was used as a feedback of participants' force production capacities. Moreover, the fatigue task was performed on the force platform to limit the amount of recovery time between the fatigue task and the postural trials in order to maximize the fatigue effects on postural control. Indeed, we

Table 2
Joints angles before (PRE) and after (POST) the fatigue protocols. YA: young adults, OA: older adults. Δ: Changes between PRE and POST. Data are presented as mean ± SD. Positive changes (Δ) in joint angles are associated with increased flexion while negative ones are associated with decreased flexion.

	Ankle (°)			Knee (°)			Hip (°)			Back (°)		
	PRE	POST	Δ	PRE	POST	Δ[b]	PRE	POST	Δ	PRE	POST	Δ[b]
YA	9.5 ± 3.3	12.6 ± 3.2	*+3.1	8.7 ± 3.7	11.2 ± 4.9	+2.5	53.1 ± 7.9	51.9 ± 8.1	−1.2	−65.5 ± 7.5	−63.5 ± 8.2	+2.1
OA	9.4 ± 3.6	11.1 ± 3.4	*+1.7	7.6 ± 3.5	9.4 ± 4.7	+1.8	50.6 ± 10.1	52.4 ± 10.3	*+1.8	−65.9 ± 6.6	−64.2 ± 6.6	+1.7

* Significant statistical difference between PRE and POST ($p < 0.05$), time × age interaction.
[b] Significant statistical difference between PRE and POST ($p < 0.05$), main time effect.

previously reported that local muscle fatigue effects on balance were recovered after 2 min [8].

4.2. Influence of fatigue and age on joint angles

Interestingly, joint angle changes with fatigue were different between young and older adults. Indeed, we observed that all joints (ankles, knees, hips and back) in older adults presented with a more flexed position after fatigue, while young adults demonstrated higher increase in ankle flexion and decreased hip flexion. These changes were accompanied by an overall anterior displacement of the COP for both age groups, as observed before [15,16]. The fact that young adults mainly adapted to fatigue by modifying their ankle joint angle could be associated with the maintenance of the ankle strategy for postural control after fatigue which confirms previous results [13,16]. On the other hand for older adults, the difficulty of the task may have been greater after fatigue and could have forced them to rely on all possible joints to maintain balance [4,13,28]. Possibly, because of the age-induced decline in force production capacity [18], the leg muscles of older adults may have more difficulty coping with the force required to adjust posture after fatigue, and therefore, a load sharing strategy among all possible joints could be used. The increased ankle dorsiflexion observed for both age groups was expected as reported before [15,17]. This postural adaptation is probably produced to limit the use of the fatigued plantarflexors while favoring the role of the intrinsic toe flexors in maintaining balance [29]. Indeed, these latter muscles have been shown to play a role in the maintenance of balance, especially at the anterior limits of postural stability, which could be reached according to the observed forward COP displacement. Furthermore, increasing dorsiflexion could increase ankle stiffness and minimize the reliance on possibly fatigue-altered sensory feedback [30]. The sensitivity of leg muscle spindles could also benefit from this increased ankle dorsiflexion [17], which could be of benefit due to the impairments in proprioception associated with muscle fatigue [31]. The increased flexion observed in other joints could allow participants to better control their balance by adding degrees of freedom to the system and consequently their options to adapt to fatigue [11]. The near-significant ($p = 0.07$) reduced flexion at the hip angle observed in young adults after fatigue is probably produced in order to limit the overall forward displacement of the COP due to the increased flexion at the other joints and avoid the fall.

4.3. Limitations of the study

The results of the present study have to be interpreted in light of some limitations. First, the relative limited number of participants in each group could limit the generalization of our results. Second, we only tested the foot together stance and it is possible that adaptations to fatigue related with age may be different for other postural tasks. Third, the fact that we did not control fatigue level may have resulted in different fatigue levels between age groups. The use of a dynamometer to assess maximal force is of interest in this topic, e.g. to assess the fatigue level. Fourth, we were able to recruit fewer older ($n = 9$) adults than younger adults ($n = 14$) which could have an influence on results by altering variability, but a limited one according to us. Finally, we did not focus on gender issues as our results did not show any differences between women and men but this topic is of interest and deserve to be further investigated.

5. Conclusion

It was found that dynamic plantarflexor fatigue similarly impaired postural control of young and older adults but was associated with different postural adaptations. Young adults presented mainly with ankle joint angle changes following fatigue, whereas older adults presented with changes at all joints. Such differences highlight the fact that postural adaptations to maintain balance are influenced by the age of the individual.

Conflict of interest statement

Authors state that there is no conflict of interest.

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