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Impairment in postural control is greater when ankle plantarflexors and dorsiflexors are fatigued simultaneously than when fatigued separately

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ABSTRACT

The aim of the present study was to compare the effects of ankle muscle fatigue on postural control when plantarflexors (PFs) and dorsiflexors (DFs) are fatigued simultaneously compared with separately. This study also investigated the recovery of postural control after fatigue. Sixteen adults (eight women and eight men) performed postural trials before and after an isokinetic fatigue task involving either (i) only PFs (30° s^{-1}), (ii) only DFs (120° s^{-1}), or (iii) both PFs and DFs simultaneously. The fatigue task involved maximal contractions repeated until the torque produced decreased below 50% of the maximal torque. Postural trials lasted 30 s and were performed on one leg with eyes open (EO) or eyes closed (EC). Sway area, medio-lateral (ML) and antero-posterior (AP) positions and velocities were calculated from the center of pressure displacements. With EO, no effect of fatigue was found on postural variables. With EC, sway area and AP velocity increased only when both PFs and DFs were fatigued simultaneously. An effect of fatigue present only when both muscle groups are fatigued simultaneously could be due to impairment in the compensatory activity between agonist and antagonist muscles and/or a greater decrease in proprioception due to a greater number of fatigued muscles. In addition, when PFs and DFs were fatigued simultaneously, sway area and AP velocity returned to pre-fatigue values within 2 min, whereas a posterior shift in AP position persisted for 10 min. This last result may suggest a longer-lasting change in postural strategy needed for optimal postural control.

1. Introduction

Postural control or balance is a prerequisite for completing activities of daily living and for the optimal performance of physical activities [1]. Postural control requires the dynamic integration and constant re-weighting of information from visual, vestibular and somatosensory systems, which control the continuous muscular corrections needed to maintain the body center of mass (COM) within the base of support [2]. In this context, the projection of the COM falls anterior to the axis of the talocrural joint, and consequently, calf muscles are considered to play a major role in postural control [3]. Indeed, it has been reported that the ankle musculature, i.e. plantarflexors (PFs) and dorsiflexors (DFs), plays a central role in maintaining balance during single and

bilateral limb stances [4]. Moreover, several studies concluded that both gastrocnemii and soleus muscles play a significant role in postural corrections, mainly in the antero-posterior plane [5]. On the other hand, Di Giulio et al. [6] suggested that the tibialis anterior muscle is a better source of proprioceptive information than the active agonists (soleus and gastrocnemius).

Muscle fatigue is a complex phenomenon involving numerous sites of the neuromuscular system [7]. Fatigue has been reported to have adverse effects on movement-related variables, including impairments in muscle contractile efficiency [8] and decreased proprioception [9]. Fatigue also affects more complex functions such as tasks involving manipulation (e.g. [10]), stopping/jumping (e.g. [11]), reaching (e.g. [12]), and of particular interest for the present study, tasks requiring the maintenance of an upright posture (e.g. [13]).

Recently, numerous studies focused on the effects of ankle muscle fatigue on postural control during standing [13–25]. Although a significant effect of muscle fatigue on posture appears predominant, results are inconsistent which may be due to methodological differences across studies (i.e. fatigue protocols,

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postural stance used, visual information available). Indeed, whereas some studies report no changes in postural control after fatigue of ankle PFs [14,17], most investigations conclude that ankle muscle fatigue negatively affects postural control. This has been shown with and without vision and regardless of the postural task tested (one- or two-leg stance) after isolated fatigue of the ankle PFs [13,15,20,24], or after simultaneous fatigue of ankle PFs and DFs [16,18,19,21–23,25]. However, a direct comparison of the effect of fatigue of these two muscle groups has not been carried out. Therefore, the main purpose of this study was to compare the effects of ankle muscle fatigue on postural sway when PFs and DFs are fatigued simultaneously compared with separately. We hypothesized that postural sway would increase more when both muscle groups are fatigued simultaneously compared with separately. This hypothesis stems from the assumption that the neuromuscular system may be able to compensate for the fatigue-related decrease in postural control more readily if at least one non-fatigued muscle group can optimally provide proprioceptive information or generate appropriate actions.

A secondary purpose was to investigate the recovery of postural control after impairment induced by ankle muscle fatigue. Post-fatigue recovery of sway features has been poorly documented in literature, with different conclusions. Some studies indicate that the effects of simultaneous fatigue of ankle PFs and DFs on postural control during unipedal stance with eyes open can persist at least 10 min [16,18,19,21–23,25]. On the other hand, Harkins et al. [19] indicated that postural control during unipedal stance with eyes closed recovered very quickly (less than a minute) after isokinetic fatigue of the same muscles. These variable results may be explained by discrepancies in experimental designs such as the duration of the fatigue protocol and the muscles fatigued. It was expected that the effects of fatigue on postural control would recover quickly as the experimental conditions of the present study are close to those of Harkins et al. [19].

2. Methods

2.1. Subjects

Sixteen (eight women and eight men) healthy adults (21.9 ± 3.5 years, 174.3 ± 8.3 cm, 69.4 ± 9.3 kg) volunteered for the present study. Subjects were clearly informed of the purpose of the study before their written consent was obtained. The research protocol was approved by the research ethics boards of the Élisabeth Bruyère Research Institute and of the University of Ottawa. None of the subjects presented with any history of injury, surgery or pathology of the lower limb that could affect their ability to perform the experiment.

2.2. Apparatus

A force platform (AMTI Acu-Gait[®], AMTI[®], Watertown, USA) was used to measure the displacements of the center of pressure (COP) during postural trials (sampling frequency: 50 Hz). An isokinetic dynamometer (Biodex System 3 Pro[®], Biodex Medical Systems,

Shirley, USA) was used to assess the maximal voluntary isokinetic torque (MVT) of ankle PFs and DFs and to perform fatigue protocols.

2.3. Experimental procedure

Subjects participated in three experimental sessions (Fig. 1) performed approximately one week apart. Sessions were identical except for the muscle group(s) fatigued: ankle PFs only, ankle DFs only, both PFs and DFs simultaneously (PFs + DFs). The order of experimental sessions was counterbalanced across subjects. During postural trials, subjects had to stand barefoot on their right leg under two vision conditions: with eyes open (EO) and with eyes closed (EC). All postural trials lasted 30 s. Subjects were instructed to sway as little as possible while standing. During these postural trials, subjects started with their arms along their body and were able to use their arms to maintain their balance. For trials performed with EO, subjects were instructed to look at a mark placed on the wall 2.5 m in front of them. For trials performed with EC, subjects were instructed to lift their left leg, find their balance, and then close their eyes.

After familiarization to the postural task, subjects sat on the dynamometer so that the hip was flexed at 70° (0° = full extension), and the knee fully extended. After a brief warm-up, subjects performed three maximal isokinetic contractions of ankle PFs (30° s^{-1}) and/or ankle DFs (120° s^{-1}) according to the experimental session. This allowed the dynamic assessment of the MVT for each velocity. Then, subjects performed eight pre-fatigue (PRE) postural trials (four for each vision condition). Afterwards, subjects performed one of the three fatigue protocols, which consisted of maximal isokinetic contractions of (i) only PFs (30° s^{-1}); (ii) only DFs (120° s^{-1}); or (iii) both PFs (30° s^{-1}) and DFs (120° s^{-1}), repeated until the torque produced decreased below 50% MVT for three consecutive contractions. Different velocities were chosen for isokinetic contractions of PFs and DFs muscles in order to reach similar time to fatigue for both muscle groups as done previously [19,26,27]. Subjects were given strong verbal encouragements during maximal contractions and all fatigue tests. Immediately after the fatigue protocol (15–20 s), subjects performed two post-fatigue (POST) postural trials, one with EO, and one with EC (order counterbalanced). Within each experimental session, the fatigue protocol and two POST trials were performed four times (Fig. 1) for a total of eight POST postural trials (four for each vision condition). The fatigue protocol was repeated after every two POST postural trials to minimize the potential rapid recovery of sway on POST data. Finally, after the last two POST trials, subjects alternated 1 min of recovery seated on a chair and two recovery (REC) postural trials (one for each vision condition), to record a total of 16 REC postural trials (eight for each vision condition). For each postural trial, subjects placed their foot at the same location on the force platform by matching a template footprint drawn on the platform.

2.4. Data analysis

COP data were used to calculate five postural variables: the area of the 95% confidence ellipse (sway area, cm^2), the mean COP

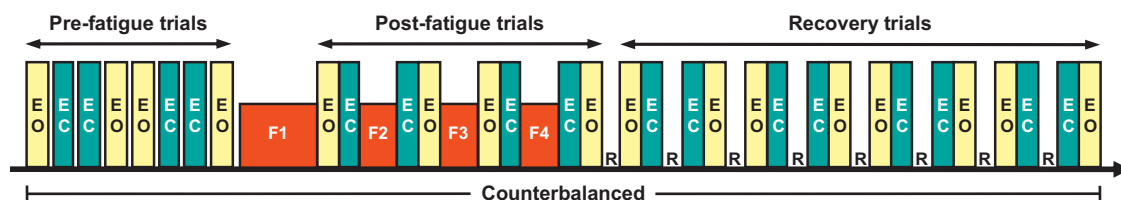


Fig. 1. Schematic representation of the experimental procedure focusing on postural trials. EO: postural trials performed with eyes open. EC: postural trials performed with eyes closed. F1–F4: fatigue protocols. R: 60-s rest period between recovery trials.

Table 1
Durations and number of contractions of the fatigue tests (mean \pm SD).

	PFs + DFs		PFs		DFs	
	Duration (s)	Number of contractions	Duration (s)	Number of contractions	Duration (s)	Number of contractions
Fatigue test 1	122.6 \pm 67.9	69.1 \pm 40.9	60.0 \pm 19.8	37.7 \pm 12.3	76.1 \pm 39.4	76.0 \pm 36.8
Fatigue test 2	90.3 \pm 48.6	53.2 \pm 31.9	56.3 \pm 19.8	36.6 \pm 12.2	75.0 \pm 52.3	82.4 \pm 62.1
Fatigue test 3	81.8 \pm 44.1	49.4 \pm 26.3	51.9 \pm 20.7	34.1 \pm 12.8	63.6 \pm 43.9	70.8 \pm 50.1
Fatigue test 4	76.8 \pm 38.5	48.6 \pm 26.2	67.6 \pm 20.4	44.4 \pm 17.2	69.2 \pm 56.4	80.7 \pm 71.1
Mean \pm SD	92.9 \pm 52.9*	55.1 \pm 42.2	58.9 \pm 28.9	38.2 \pm 15.4	71.0 \pm 47.6	77.5 \pm 43.1*

* Significantly different ($p < 0.05$) from PFs session.

position and the mean sway velocity in the medio-lateral (ML position, cm; ML velocity, cm s^{-1}) and antero-posterior (AP position, cm; AP velocity, cm s^{-1}) directions. These variables are frequently assessed in postural control studies and have good validity and reliability [28]. During a postural trial, when a step occurred, the trial was removed from data analysis. This represented 5% of the total number of trials (i.e. 75 trials out of a total of 1536 trials). However, statistical analyses including postural trials where subjects took a step led to similar results as those presented hereafter.

2.5. Statistical analysis

First, two-way analyses of variance (ANOVA) for repeated measures were used to assess the effects of the muscle group involved during the fatigue tests (PFs + DFs, DFs, PFs) and the effects of the fatigue test number (test 1, test 2, test 3, test 4) on the duration and on the number of contractions of the fatigue tests. Second, three-way ANOVAs for repeated measures were used to assess the effects of vision (EO, EC), fatigue (PRE, POST), and muscle group (PFs + DFs, DFs, PFs) on the five postural variables (sway area, ML and AP positions, ML and AP velocities). Third, two-way ANOVAs for repeated measures were used to assess the effects of fatigue (PRE, POST) and muscle group (PFs + DFs, DFs, PFs) on the five postural variables, considering postural trials performed with EC and EO separately. Fourth, considering the results of the task with the greatest fatigue-related changes in postural control (i.e. PFs + DFs with EC), one-way ANOVAs for repeated measures were used to assess the effect of fatigue and recovery (PRE, POST, REC1 to REC8) on the postural variables. For all statistical tests, the significance level was set at 0.05. When relevant, *post hoc* tests were performed by means of Newman–Keuls procedures. When the sphericity assumption in repeated measures ANOVAs was violated (Mauchly's test), a Geisser/Greenhouse correction was used.

3. Results

3.1. Fatigue tests characteristics

The two-way ANOVAs (muscle group \times test number) revealed a main effect of the muscle group for the duration and the number of

contractions of the fatigue tests. The duration of the fatigue test was significantly ($p < 0.05$) longer for the PFs + DFs session (92.9 \pm 52.9 s) than for PFs sessions (58.9 \pm 28.9 s). There was no difference between DFs sessions (71.0 \pm 47.6 s) and PFs + DFs or PFs sessions (Table 1). The number of contractions performed during the DFs sessions (77 \pm 43) was significantly ($p < 0.05$) higher than the one of the PFs sessions (38 \pm 15). There was no difference between PFs + DFs (55 \pm 42) and DFs or PFs sessions (Table 1).

3.2. Influence of the muscle group fatigued on postural control with eyes open or eyes closed

3.2.1. Main effect of vision

The three-way ANOVAs (vision \times fatigue \times muscle group) revealed a main effect of vision for sway area, ML velocity, and AP velocity (Table 2). Mean values of these postural variables were significantly ($p < 0.001$) higher for postural trials performed with EC than with EO.

3.2.2. Main effect of fatigue

The three-way ANOVAs (vision \times fatigue \times muscle group) revealed a main effect of fatigue for sway area, AP velocity, and AP position (Table 2). Mean values of sway area and AP velocity were significantly ($p < 0.01$) higher for POST postural trials than PRE trials. The AP position significantly ($p < 0.01$) shifted backward after fatigue.

3.2.3. Interaction of vision by fatigue

The three-way ANOVAs (vision \times fatigue \times muscle group) revealed an interaction between fatigue and vision for sway area, and AP velocity (Table 2). With EO, sway area POST was 7% higher than PRE (9.8 \pm 3.3 cm^2 vs. 9.2 \pm 2.7 cm^2 , $p < 0.01$). With EC, sway area POST was 14% higher than PRE (24.2 \pm 6.1 cm^2 vs. 21.3 \pm 5.0 cm^2 , $p < 0.001$). With EO, AP velocity POST was 6% higher than PRE (2.2 \pm 0.5 cm s^{-1} vs. 2.1 \pm 0.5 cm s^{-1} , $p = 0.003$). With EC, AP velocity POST was 9% higher than PRE (4.4 \pm 1.0 cm s^{-1} vs. 4.0 \pm 1.0 cm s^{-1} , $p < 0.001$).

3.2.4. Interaction of vision by muscle group

The three-way ANOVAs (vision \times fatigue \times muscle group) revealed an interaction between muscle group and vision for

Table 2
Results of the three-way ANOVAs (vision \times fatigue \times muscle group) for the five postural variables.

	Sway area		ML velocity		AP velocity		ML position		AP position	
	F	p	F	p	F	p	F	p	F	p
Vision (V)	119.3	<0.001	146.7	<0.001	98.6	<0.001	ns		ns	
Fatigue (F)	15.5	0.004	ns		29.4	<0.001	ns		21.2	0.002
Muscle group (MG)	ns		ns		ns		ns		ns	
V \times F	35.6	<0.001	ns		22.1	0.002	ns		ns	
V \times MG	4.9	0.022	ns		ns		ns		ns	
F \times MG	ns		ns		ns		ns		ns	
V \times F \times MG	ns		ns		ns		ns		ns	

ns: non significant.

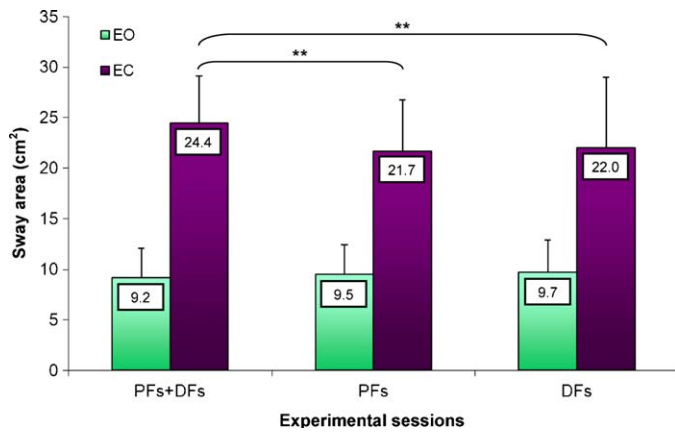


Fig. 2. Sway area \pm SD recorded during the three experimental sessions (PFs + DFs, PFs, DFs) performed with eyes open (EO) and with eyes closed (EC). **Significant differences between experimental sessions ($p < 0.01$). The significant ($p < 0.001$) differences between EO and EC trials of the same experimental sessions were not represented for clarity.

sway area. With EO, there was no significant difference in sway area between the three experimental sessions ($p > 0.05$). With EC, sway area during the PFs + DFs session ($24.4 \pm 4.7 \text{ cm}^2$) was 13% and 11% higher than the sway area recorded during DFs ($21.7 \pm 5.1 \text{ cm}^2$, $p = 0.008$), and PFs ($22.0 \pm 6.9 \text{ cm}^2$, $p = 0.004$) sessions, respectively (Fig. 2).

These last two interactions (vision \times fatigue and vision \times muscle group) suggested that the effects of fatigue and/or differences across the three sessions depended on the vision condition. Thus, further statistical analyses were performed separating postural trials performed with EC vs. EO.

3.3. Fatigue \times muscle group analyses (trials performed with EC and EO are separated)

3.3.1. Postural trials performed with EO

The two-way ANOVAs (fatigue \times muscle group) revealed neither main effects nor interactions for the five postural variables.

3.3.2. Postural trials performed with EC

3.3.2.1. Sway area. A main effect of fatigue ($F = 39.4$, $p < 0.001$) and a fatigue \times muscle group interaction ($F = 4.4$, $p < 0.02$) were found significant for sway area. Sway area POST was not different from PRE for PFs and DFs sessions ($p > 0.05$), whereas it was 25% higher for the PFs + DFs session ($27.1 \pm 4.3 \text{ cm}^2$ vs. $21.8 \pm 3.5 \text{ cm}^2$, $p < 0.001$, Fig. 3A).

3.3.2.2. AP and ML velocity. A main effect of fatigue ($F = 24.8$, $p < 0.001$) and a fatigue \times muscle group interaction ($F = 3.8$, $p < 0.03$) were found significant for AP velocity, whereas neither main effects nor interactions were found for ML velocity. AP velocity POST was not different from PRE for PFs and DFs sessions ($p > 0.05$), whereas it was 17% higher than PRE for the PFs + DFs session ($4.7 \pm 1.0 \text{ cm s}^{-1}$ vs. $4.0 \pm 1.0 \text{ cm s}^{-1}$, $p < 0.001$, Fig. 3B).

3.3.2.3. AP and ML position. A main effect of fatigue ($F = 70.7$, $p < 0.001$) was found for AP position whereas neither main effects nor interactions were observed for ML position. AP position moved posteriorly by about 1 cm from PRE to POST ($0.0 \pm 1.4 \text{ cm}$ vs. $-1.1 \pm 1.5 \text{ cm}$, $p < 0.001$).

3.4. Recovery

One-way ANOVAs revealed a main effect of time for sway area ($F = 7.4$, $p < 0.001$), AP velocity ($F = 12.4$, $p < 0.001$), and AP

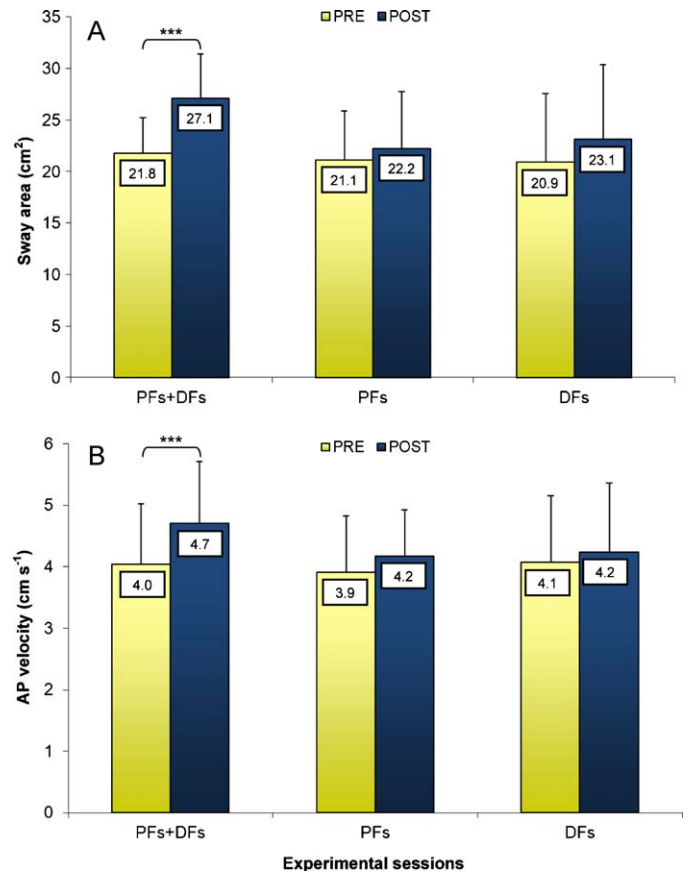


Fig. 3. Sway area \pm SD (A) and AP velocity \pm SD (B) recorded during the three experimental sessions (PFs + DFs, PFs, DFs) performed with eyes closed before (PRE) and after (POST) the fatigue protocol. ***Significant differences between PRE and POST ($p < 0.001$).

position ($F = 13.5$, $p < 0.001$). For sway area (Fig. 4A) and AP velocity (Fig. 4B), POST values were higher than PRE ($p < 0.001$), whereas all recovery values (R1–R8) were not different from PRE ($p > 0.05$). For AP position (Fig. 4C), the POST and first six recovery values were different from PRE ($p < 0.001$).

4. Discussion

The aim of the present study was to compare the effects of ankle muscle fatigue on postural sway during quiet unipedal standing, with and without vision, when PFs and DFs were fatigued simultaneously or separately. Our main results revealed that postural control is impaired to a greater extent when ankle PFs and DFs are fatigued simultaneously compared with separately, but only when visual information is removed. We also observed that sway area and AP velocity returned to baseline within 2 min, whereas AP position remained altered for 10 min.

4.1. Effects of vision and fatigue

As found by others [13,15,20], postural sway area and AP velocity increased when vision was removed, which indicates the importance of visual information for postural stability. Our results also revealed that fatigue of the ankle musculature, regardless of the fatigued muscle groups, altered postural sway and AP velocity, which was expected and in accordance with literature (e.g. [16,18,19]). The impairment of postural control after fatigue may be related to alterations in both sensory and motor processes, such as impaired proprioception [29], and an altered ability to produce

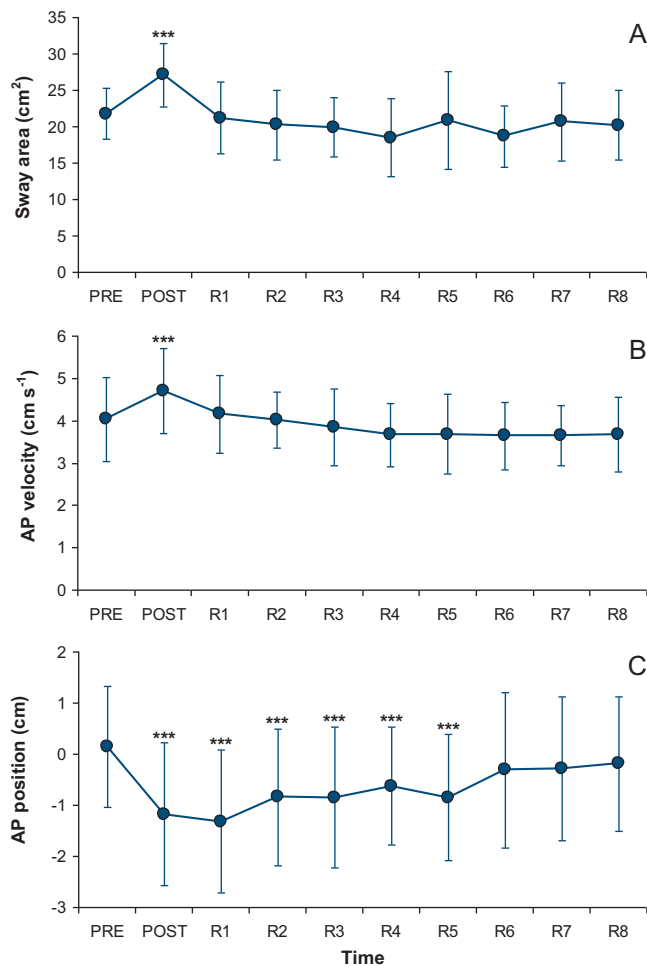


Fig. 4. Changes in sway area \pm SD (A), AP velocity \pm SD (B), and AP position \pm SD (C) for the PFs + DFs experimental session, eyes closed condition. PRE: pre-fatigue data. POST: post-fatigue data. R1–R8: data recorded after the first to the eighth recovery periods. ***Significantly different from other data ($p < 0.001$). Considering AP position, positive changes indicate a forward displacement of the COP whereas negative changes indicate a backward displacement.

force [30]. These alterations could lead to inappropriate or delayed stabilizing muscle activation, leading to a decrement in postural control [31].

More precisely, the interaction between vision and fatigue revealed that after the fatigue protocol, sway area and AP velocity increased by 7% and 6% respectively with EO, whereas increases were 14% and 9% with EC. Thus, the fatigue effect on postural control appears greater with no vision. These results are in accordance with previous studies [13,32] and suggest that vision can compensate for the impaired postural control due to muscle fatigue. The compensatory role of vision in the maintenance of postural control was further supported by the results of the two-way ANOVAs (fatigue \times muscle group) performed on the data from postural trials performed with EO, where no effect of fatigue was found regardless of the muscle group(s) fatigued [14,17].

We observed no effect of fatigue for ML velocity and ML position. This is in accordance with another study reporting an effect of fatigue in the AP but not the ML direction after ankle PFs and DFs fatigue [18]. This can appear surprising, as muscles producing inversion and eversion also take part in plantarflexion and dorsiflexion. For example, the extensor hallucis longus contributes to dorsiflexion and inversion, and the peroneus longus to plantarflexion and eversion. Possibly, muscles primarily involved in the control of COP sway in the ML direction (ankle

invertors and evertors) were not fatigued enough (because they were not prime movers) by our fatigue protocol to induce a significant impairment in ML velocity and position.

4.2. Effect of the muscle group fatigued

Considering the characteristics of the fatigue tests, one may have expected greater fatigue effects for the PFs + DFs session, because it was associated with longer durations. However, considering the facts that: (1) the criterion to end the fatigue task was the same in the three sessions, (2) the duration of the tasks was not different between the PFs + DFs and DFs sessions, and (3) the number of contractions was higher in the DFs compared with PFs + DFs session; we believe that the differences in the fatigue effects between the three sessions were mainly due to the muscle group(s) fatigued (PFs only, DFs only, and PFs + DFs).

As mentioned above, there was no effect of fatigue for any of the sessions (PFs + DFs, PFs, DFs) when considering the EO condition. When considering data from the EC condition, our results revealed that sway area and AP velocity collected after the fatigue of only one muscle group were not significantly different from those collected before fatigue (Fig. 3). In contrast, these two variables were respectively 25% and 17% higher than PRE when both muscle groups were fatigued simultaneously. To our knowledge, our study is the first to compare the effects on postural control of fatiguing ankle PFs and DFs separately or simultaneously. Our results suggest that postural control is impaired to a greater extent when both muscle groups are fatigued simultaneously compared with separately which confirms our hypothesis. We offer two explanations for this result. First, the neuromuscular system may be able to more readily compensate for the impaired postural control following fatigue of a single muscle group relying on the antagonist muscle group, whereas this would be not possible (or to a lesser extent) if both muscle groups are fatigued. Such compensatory activity between synergist muscles after specific fatigue of one or several muscles has been reported before [33,34]. These authors have suggested that fatigue of one synergist muscle can induce changes in the supraspinal activity regulating the activity of the other muscle(s). Secondly, one can assume that with more muscles fatigued, the proprioception impairment associated with fatigue could be more important and consequently lead to a greater decrease in postural control.

4.3. Recovery of postural variables

The other aim of the present study was to document the duration of the transient effect of ankle muscle fatigue on postural control. To address this objective, we only considered the experimental session that induced the greatest fatigue effects, i.e. the PFs + DFs session.

Results indicated that sway area and AP velocity were altered by the PFs + DFs fatigue protocol and returned to pre-fatigue values within 2 min (Fig. 4). These results are similar to those of Harkins et al. [19] who reported that sway velocity was impaired for approximately 35 s after the same fatigue protocol. On the other hand, our results are different from those of others who report that fatigue effects persist at least 10 min [22,25]. These differences could be explained by the discrepancies in implemented fatigue protocols. Indeed, fatigue in these later studies was of either long duration (i.e. 25 min [22]), or involved muscle groups acting in both sagittal and frontal planes [25]. In our protocol, the medial–lateral stabilizers of the ankle joint were not fatigued, and may have compensated for anterior–posterior stabilizers fatigue [19]. The short duration of the effect of muscle fatigue on postural control could thus be due to the nature of the fatigue protocol (maximal isokinetic concentric contractions) that induced mainly

peripheral fatigue that is restored quickly. For example, it has been reported that force was restored within 2 min after isometric contractions sustained until force declined below 50% MVC [35].

Our results indicated that changes in AP position due to fatigue persisted longer (more than 10 min) than for the other variables. More specifically, fatigue induced a posterior shift of the COP. In contrast, Vuillerme et al. [24] reported that the COP position shifted forward after fatigue of ankle PFs, but for a bilateral stance task. Thus, the shift in COP position, which may suggest a longer-lasting change in the strategy needed for optimal postural control, appears to be task-specific. One possible explanation for a posterior shift in the mean position of the COP is that subjects may have changed their overall posture after fatigue. With ankle muscles fatigued, particularly the PFs which are important contributors to postural corrections, a posterior shift of the COP effected through a change in ankle, knee and/or hip angles, could reduce the demands or reliance placed on this muscle group for optimal control. This may be associated with a possible change, for example, to a more predominant hip control strategy.

5. Conclusion

The postural control of unipedal stance was more impaired when ankle PFs and DFs were fatigued simultaneously compared with separately. This observation was only true with eyes closed, as vision alleviated the instability induced by fatigue. Moreover, different posture control variables recovered at different rates following fatigue of ankle PFs and DFs.

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Conflict of interest

None of the authors have ties to any activity or industry that could inappropriately influence his judgment regarding this research or the results presented in the manuscript.

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