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Influence of ankle plantarflexor fatigue on postural sway, lower limb articular angles, and postural strategies during unipedal quiet standing

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ABSTRACT

The purpose of this study was to investigate the changes in postural control and in posture induced by ankle plantarflexor fatigue during a unipedal stance task. We also studied the postural strategies in the antero-posterior and medio-lateral planes used by participants to maintain balance. Thirteen young adults were asked to stand barefoot on their preferred leg as still as possible for 30 s with vision or without vision. Participants performed postural trials before and after a fatigue protocol that consisted of standing on toes until exhaustion. Centre of pressure (COP) displacements were measured with a force platform and electrogoniometers were placed at the ankle, knee and hip joints of the support leg to monitor articular angles. Relationships between changes in articular angles and displacements of the COP in the antero-posterior and medio-lateral planes were tested using cross-correlations. Sway area and velocity increased with fatigue, but only without vision. A posterior shift of the mean COP position was also observed after fatigue. Ankle and hip joints were more flexed after fatigue. Moderate to good relationships between COP displacements and ankle angles were observed before and after fatigue in both planes whereas these relationships were low for hip and knee joints. Ankle plantarflexors fatigue induced impairment in postural control and changes in posture. To compensate for the effects of fatigue, participants increased the flexion of the ankle and/or the hip joints but conserved the ankle strategy as the dominant postural strategy in both planes.

1. Introduction

Numerous studies have reported an impairment of postural control during quiet standing after the performance of a fatiguing motor task involving different joints such as the hip [1], knee [2], and ankle [3]. The ankle joint is particularly of interest because, during quiet standing, the projection of the centre of mass falls anterior to the axis of the talocrural joint. Consequently, calf muscles are considered to play a major role in postural control [4]. Indeed, it has been reported that the ankle musculature plays a central role in maintaining balance during single and bilateral limb stances [5,6] and that plantarflexors play a significant role in postural corrections, mainly in the antero-posterior plane [7].

Fatigue has generally been found to increase sway [8], which is typically documented through variables calculated from the displacements of the centre of pressure (COP). Sway-related postural variables provide important information about postural stability and control [9], but their ability to illustrate changes in body segments configuration (i.e., position of the limbs/articular angles) is limited [10]. Several studies have investigated the effects of fatigue on limb position during various tasks such as walking [11] or reaching [12]. However, to our knowledge, only one study has documented the changes in limb position/articular angles during quiet standing after fatigue [13]. In this study, focusing on bipedal stance, lumbar extensor fatigue induced an anterior shift of the COP which was associated with greater ankle dorsiflexion. An anterior shift of the COP has also been reported by Vuillerme et al. [14] after fatigue of the ankle plantarflexors for a similar bilateral stance task. During unipedal stance, only Lundin et al. [15] reported this finding, and suggested that this anterior shift of the COP may be due to an increased role of the intrinsic toe flexors in maintaining balance. Indeed, these muscles have been shown to play a role in the maintenance of balance, especially at the anterior limits of postural stability [16]. In contrast, we recently observed a posterior shift of the COP after ankle plantarflexor fatigue during a unipedal stance task [17]. We assumed that this could be explained

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by a change in ankle, knee and/or hip articular angles in order to reduce the demands or reliance placed on the fatigued plantarflexors for optimal stability. However, with only COP data available, we were not able to verify this assumption.

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 [18,19]. These sagittal plane strategies have been widely studied in contrast to those occurring in the medio-lateral plane. Hoogvliet et al. [20] proposed that the two major mechanisms for medio-lateral plane postural control are the foot-tilt strategy [21] and the hip strategy [22]. 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 [23], whereas participants may employ the hip strategy during more challenging tasks [6,24]. Neuromuscular fatigue is also one factor influencing the difficulty of the postural task, but few studies have focused on the effect of fatigue on postural strategies, and only on the antero-posterior plane strategies. Considering bipedal quiet standing, Madigan et al. [13] reported that participants used mainly the ankle strategy before and after lumbar extensor fatigue. However, fatigue-related changes in antero-posterior plane strategies have yet to be documented following fatigue of the ankle musculature, and there is no literature on the effect of fatigue on medio-lateral plane postural strategies.

The first aim of the present study was to investigate the changes in postural control and articular angles induced by ankle plantarflexor fatigue during a unipedal stance task. It was hypothesized that muscle fatigue would be associated with an impairment of postural control illustrated by increased sway area and velocity. We also hypothesized that muscle fatigue would induce a posterior shift of the COP associated with changes in hip, knee and/or ankle angles. The second aim was to investigate the effect of fatigue on postural strategies used to maintain stability during unipedal quiet standing. We hypothesized that the ankle strategy would be the main strategy used by participants before fatigue in both planes [25] and that fatigue would induce a greater use of the hip strategy as the postural task becomes more challenging post-fatigue.

2. Methods

2.1. Participants

Thirteen (eight women and five men) healthy adults (21.4 ± 4.6 years, 168.9 ± 12.9 cm, and 67.1 ± 14.0 kg) volunteered for the present study. The research protocol was approved by the research ethics boards of the Élisabeth Bruyère Research Institute and the University of Ottawa. None of the participants 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 AccuGait®, AMTI®, Watertown, USA) was used to measure the displacements of the COP during postural trials (sampling frequency: 100 Hz). Three electrogoniometers (Biometrics Ltd., Ladysmith, USA) were placed on the support lower limb to assess changes in ankle, knee and hip articular angles during postural trials (over a range of ±90°, accuracy: ±2°, repeatability: 1°; sampling frequency: 100 Hz).

2.3. Experimental procedure

Participants performed postural trials before and immediately after fatigue protocols (Fig. 1). During postural trials, participants had to stand barefoot on their preferred leg with their eyes open (EO) or closed (EC). Participants began postural trials with their hands at the hips and were instructed to sway as little as possible. All postural trials lasted 30 s. For trials performed with EO, participants were instructed to look at a mark placed at eye level, 2.5 m in front of them. For trials performed with EC, participants had to find their balance before closing their eyes. The order of the postural trials was counterbalanced amongst participants.

After familiarization with the postural tasks, participants performed eight pre-fatigue (PRE) postural trials including four with EO and four with EC. Then, participants were required to stand on the tip of the toes of their support leg and to extend (plantarflexion) their ankle joint as much as possible for three times separated by 1 min of rest. The maximal value obtained from the ankle goniometer during that maximal plantarflexion movement was set as the maximal articular amplitude of the ankle. Afterwards, participants performed the fatigue protocol that consisted in maintaining the greatest ankle articular angle as long as possible until this angle decreased below 25% of the maximal amplitude. Immediately after the fatigue protocol, participants performed two post-fatigue (POST) postural trials, one with EO, and one with EC that were separated by less than 5 s to minimize recovery effects. This sequence (i.e., one fatigue protocol and two post-fatigue postural trials) was repeated four times to obtain eight POST trials, four with EO and four with EC.

2.4. Data analysis and statistics

COP data were used to calculate five postural variables: the area of the 95% confidence ellipse (sway area, cm^2), the mean COP position and the mean sway velocity in the antero-posterior (AP position, cm; AP velocity, cm s^{-1}) and medio-lateral (ML position, cm; ML velocity, cm s^{-1}) directions. Neutral articular angles (0°) were associated with the anatomical reference position. Changes in angles were expressed in degrees of flexion from this reference position. Cross correlations were used to assess the relationships between COP displacements and changes in articular angles, mainly to provide information about postural strategies. Peak values of the cross correlation function were used for statistical analyses. The cross correlations were performed using the entire 30 s of data for a given trial and evaluated between: (1) AP ankle angle and AP COP position; (2) AP knee angle and AP COP position; (3) AP hip angle and AP COP position; (4) ML ankle angle and ML COP position; and (5) ML hip angle and ML COP position. Relationships including the knee joint in the medio-lateral plane were not included in the analysis as movements about this joint are negligible in this plane [20].

Two-way analyses of variance (ANOVA) for repeated measures were used to assess the effects of vision (EO and EC) and fatigue (PRE and POST) on postural variables and on cross correlation values. Three-way ANOVAs for repeated measures were used to assess the effects of vision (EO and EC), fatigue (PRE and POST), and joint (hip, knee, and ankle) on joint angles (degrees of flexion). 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.

3. Results

3.1. Postural variables

The two-way ANOVA revealed a vision × fatigue interaction ($F(1,12) = 6.4$, $P < 0.05$) for sway area. Sway area POST (44.11 ± 27.09 cm^2) was 46.2% higher ($P < 0.01$) than PRE (30.17 ± 16.29 cm^2) with EC, whereas, no significant difference was observed with EO (Fig. 2).

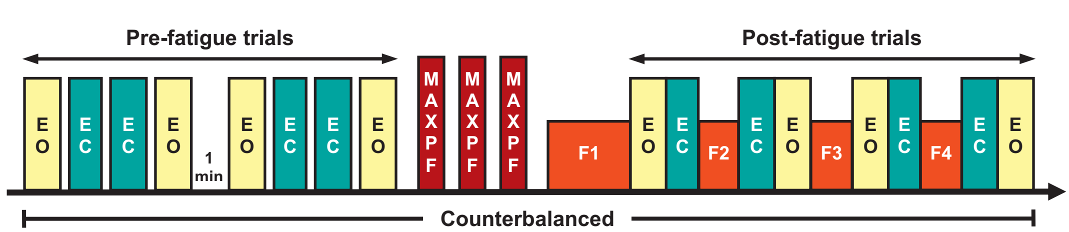

Fig. 1. Experimental procedure. EO: postural trials performed with eyes open. EC: postural trials performed with eyes closed. MAXPF: assessment of the maximal articular angle of the ankle in plantarflexion. F1–F4: fatigue protocols.