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Biomechanical reorganisation of stepping initiation during acute dorsiflexor fatigue

E. Yiou *, S. Ditcharles, S. Le Bozec

EA 4532, Laboratory CIAMS, Team RIME, UFR STAPS, University of Paris-Sud, 91440 Orsay Cedex, France

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ABSTRACT

During voluntary step initiation (SI), propulsive forces are generated during anticipatory postural adjustments (APA) which displace the centre-of-gravity (CoG) in the desired direction. These propulsive forces are implemented by ankle synergy, bilateral *soleus* inhibition followed by activation of *tibialis anterior* (TA). The aim of this study was to investigate the effect of fatigue applied to ankle dorsiflexors on APA associated with SI and on related motor performance. Eight young healthy participants initiated stepping before and after a protocol designed to generate fatigue in ankle dorsiflexors. Fatigue was induced by series of high-level isometric contractions performed until exhaustion. Results showed that, with fatigue, the level of TA activation during APA, anticipatory postural dynamics (backward centre-of-pressure displacement and forward CoG velocity) and related motor performance (peak of CoG velocity) were attenuated, while APA duration and total SI duration increased. These changes were interpreted as reflecting a protective strategy aiming to preserve the integrity of the fatigued muscles, rather than an impairment associated with muscle weakness.

1. Introduction

Since the pioneering work of Belenkii et al. (1967), it has been known that voluntary movements are preceded by dynamic and electromyographical (EMG) phenomena in the body segments composing the "postural chain" (Bouisset and Zattara, 1987; Cordo and Nashner, 1982; Massion, 1992). These phenomena are termed "anticipatory postural adjustments" (APA). When the motor task does not involve whole-body progression (e.g. during arm raising from a quiet standing posture), APA tend to create inertial forces which, when the time comes, counterbalance the perturbation to postural equilibrium due to the forthcoming intentional movement, i.e. they serve stabilising purposes (Bouisset and Zattara, 1987; Bouisset and Do, 2008). When the motor task involves whole-body progression, APA may not be exclusively devoted to body stabilisation. For instance, during step initiation (SI), voluntary stepping is preceded by a shift of the centre-of-pressure (CoP) both laterally, towards the forthcoming swing leg to stabilise the centre-of-gravity (CoG) during step execution, but also backward, to propel the CoG forward and reach the intended CoG velocity at the end of the step (Brenière et al., 1987). This anticipatory postural dynamics is presumed to be implemented by ankle synergy, characterized by bilateral *soleus* inhibition followed by strong *tibialis anterior* (TA) activation (e.g. Crenna and Frigo, 1991; Lepers and Brenière, 1995).

The question as to how APA are modified in order to take into account the internal perturbation induced by postural muscle fatigue (hereafter referred to as "fatigue") has been addressed in several recent studies (Allison et al., 2002; Kanekar et al., 2008; Morris and Allison, 2006; Strang et al., 2009; Strang and Berg, 2007; Vuillerme et al., 2002). In these studies, participants performed series of discrete motor tasks with one or both arms from a bipedal stance, before and after a fatiguing procedure designed to generate fatigue in postural muscles (legs and/or trunk). The fatiguing procedure typically consisted of series of low- to moderate-level isometric contractions (IC) – i.e. ranging from 7% of maximal voluntary isometric contraction (MIC) to 50% MIC – performed until exhaustion. These studies repeatedly reported that, under such experimental conditions, APA onset occurred earlier in the fatigued muscles, resulting in longer APA duration. Because the amplitude of the anticipatory CoP displacement and the focal movement performance remained unchanged with fatigue, this longer APA duration was thought to reflect an adaptive change aimed to compensate for the reduced capability of force production in the postural muscle system.

In contrast with these latter studies (Allison et al., 2002; Kanekar et al., 2008; Morris and Allison, 2006; Strang and Berg, 2007; Strang et al., 2009; Vuillerme et al., 2002), recent papers reported that APA onset in the fatigued (hamstrings) muscles did not occur earlier when fatigue was induced by series of high-level IC (60% MIC) (Yiou et al., 2009a; Mezaour et al., 2010). Probably as a consequence, the amplitude of the anticipatory postural dynamics (as measured with CoP and CoG measures) was drastically reduced in the fatigue condition. To explain this discrepancy with the literature, it was proposed

* Corresponding author. Tel.: +33 1 69 15 43 15; fax: +33 1 69 15 62 22.
E-mail address: e.yiou@libertysurf.fr (E. Yiou).

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that, when fatigue is induced by high-level IC (HIC) series, the adaptability of APA features to the fatigued state of the postural muscle system might be altered (Mezaour et al., 2010).

Although contributing to literature, these later studies provide an incomplete picture of the effects of fatigue on postural control during voluntary movement. Indeed, these studies used exclusively motor tasks involving forward upper limb movements from a quiet standing posture. APA duration for such motor tasks (typically a few tens of ms for a unilateral pointing task; e.g. Bouisset and Zattara, 1987; Yiou et al., 2007) is much shorter than for motor tasks involving whole-body displacement, e.g. SI (typically around 500 ms; e.g. Brenière et al., 1987; Yiou et al., 2007). Consequently, the opportunity to adapt the spatio-temporal features of APA to muscle fatigue is *a priori* much greater for SI than for upper limb movements. This statement might be of particular importance when the capacity to adapt to fatigue is altered following fatiguing HIC series (Mezaour et al., 2010). Furthermore, APA amplitude (in terms of anticipatory CoP displacement and CoG acceleration), the level of ankle dorsiflexor activation and ankle joint movement during APA are much greater for SI than for upper limb tasks (e.g. Yiou et al., 2007). The ankle joint complex is therefore solicited much more during APA for SI and thus, is more subject to damage in a fatigued state. During SI performed under a fatigued state of the ankle dorsiflexors, the anticipatory postural dynamic and the related motor performance (i.e. the "motor outcome") may therefore not remain invariant, as has been described in the literature on upper limb task, but might rather be attenuated to protect the fatigued ankle joint complex from alteration.

The goal of this study is to investigate the effect of ankle dorsiflexor fatigue induced by HIC series on APA associated with SI and on related motor performance. Decreased level of electrical activity in both TA, along with slower movement performance (longer total SI duration and slower peak CoG velocity), are expected to occur with fatigue. Such changes would argue in favour of a "protective strategy" aiming to preserve ankle dorsiflexor integrity, and would argue against the existence of a "compensatory strategy" aiming to obtain invariant motor outcome.

2. Materials and methods

2.1. Subjects

The study was performed on eight right-handed young healthy participants (five males, three females; 24 ± 3 years; 61 ± 8 kg; 168 ± 6 cm). All gave written consent after having been informed as to the nature and purpose of the experiment which was approved by local ethics committees. The study complied with the standards established by the Declaration of Helsinki.

2.2. Experimental task and conditions

The experimental task was inspired by previous papers from our laboratory (Yiou et al., 2007; Yiou and Schneider, 2007; Yiou and Do, 2010). Participants stood barefoot in a natural upright posture, feet shoulder-width apart, with the arms alongside the trunk and the gaze directed forward to a small target at eye level and out of reach (2 cm diameter, 3 m distant). The location of each foot in the initial posture was marked on millimetric paper placed over the force plate. These marks were used as a visual reference on which participants positioned themselves under the supervision of the experimenters.

Participants performed ten trials under each of the two following conditions: under the "no fatigue" condition (NF), participants initiated a forward step with the preferred leg; under the "fatigue" condition (F), participants initiated a forward step after a fatiguing procedure designed to obtain major fatigue in the ankle dorsiflexors. Under these two conditions, SI was performed at a spontaneous velocity following an auditory Go signal. In four participants, stepping was also performed at maximal velocity in F. This pilot condition was carried out to check that participants were able to increase the level of anticipatory TA activity in F and obtain greater APA amplitude (see below for detailed description of these variables) as compared to spontaneous SI. These two conditions (spontaneous and maximal SI velocity) were randomized across these participants. A single step was performed in each condition. In the final posture, the swing foot was placed in front of the stance foot. This final posture was used in previous studies to elicit large stepping APA (e.g. Do and Yiou, 1999). It was used here to elicit the shortest trial duration as possible (as participants did not have to bring the stance leg forward) with the purpose to obtain a constant level of TA fatigue in F trials. The duration of whole trials in F was 50 ± 7 s for SI at spontaneous velocity and 53 ± 6 s for SI at maximal velocity. There was no instruction regarding step length. One blank trial was provided in NF (not recorded).

2.3. Fatiguing procedure

The fatiguing procedure was inspired by previous studies from our laboratory (Yiou et al., 2009a; Mezaour et al., 2010). Participants lay in a semi-recumbent position with their legs outstretched and their feet placed in a customized apparatus designed to obtain major fatigue in ankle dorsiflexors (Fig. 1A). Ankle dorsiflexors were targeted for fatigue because they play a predominant role in anticipatory CoP motion (e.g. Lepers and Brenière, 1995). Before the fatiguing procedure, participants warmed up for 10 min on an ergocycle at slow speed, then performed three successive isometric ankle dorsiflexions at a low force level in the fatiguing apparatus. During these IC, the ankles were flexed 100°. The ankle joint angle was monitored on line with an electrogoniometer (Penny and Gilles; ±1° precision) placed on the right side of the body. The maximal voluntary isometric ramped contraction (MIC) to be exerted with ankles dorsal flexed 100° was then evaluated for a first time (MIC1). MIC corresponded to the highest isometric force that could be exerted in three successive three-second trials with one minute's rest in between. Then, series of 30 seconds isometric ramped contractions at 60 ± 2% MIC1 ("fatiguing-series"; range variation allowed: 58–62% MIC1), immediately followed by 15 s rest, were repeated until the required fatigue level was obtained. MIC was then re-evaluated (MIC2). For the four participants who performed the pilot condition, fatiguing series were also included between the two SI conditions (spontaneous and maximal velocity) to ensure that TA did not recover from fatigue.

Fatigue has been defined as "a reduction of maximal muscle force or power that occurs with exercise" (Taylor et al., 2000). The decrease of force between MIC2 and MIC1 was therefore considered here as an indicator of fatigue. Subjects could visualize the force level they exerted during the IC series on the screen of an oscilloscope (Fig. 1A). Fatigue occurred when participants could not maintain the targeted force for fifteen consecutive seconds (during this time, the force remained below 58% MIC1). During the fatiguing procedure, participants were strongly encouraged by the experimenters to maintain the targeted force. Participants were sped up to recover their feet' marks on the force-plate immediately after the fatiguing procedure. The fatiguing series took place beside the force-plate to ensure minimal time between the end of the fatiguing procedure and the beginning of the first SI trial in F (the mean time was 10 ± 3 s). With these precautions, we ensured that participants did not recover from fatigue in F.

During IC series, force was exerted by the dorsal part of the feet against a light aluminium bar wrapped in foam to prevent discomfort (Fig. 1A). The force exerted by each ankle joint was measured