Journal of Biomechanics 46 (2013) 1676–1682

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Changes in stationary upright standing and proprioceptive reflex control of foot muscles after fatiguing static foot inversion

Bruno Vie [a], Nicolas Gomez [b], Christelle Brerro-Saby [a], Jean Paul Weber [a], Yves Jammes [b,*]

[a] Ecole de Podologie de Marseille, Marseille, France
[b] UMR MD2, Faculty of Medicine, Aix-Marseille University, Marseille, France

ARTICLE INFO

Article history:
Accepted 8 April 2013

Keywords:
Posture
Foot muscles
Muscle fatigue
Proprioceptive reflex
Hoffman reflex

ABSTRACT

We searched for the consequences of a maximal static foot inversion sustained until exhaustion on the post-exercise stationary upright standing and the proprioceptive control of the foot muscles.

Twelve healthy subjects executed an unilateral maximal static foot inversion during which continuous power spectrum analyses of surface electromyograms of the *tibialis anterior* (TA), *peroneus longus* (PL), and *gastrocnemius medialis* (GM) muscles were performed. Superimposed pulse trains (twitch interpolation) were delivered to the TA muscle to identify "central" or "peripheral" fatigue. Before and after the fatiguing task, we measured (1) the repartition of the plantar and barycentre surfaces with a computerized stationary platform, (2) the peak contractile TA response to electrical stimulation (TA twitch), (3) the tonic vibratory response (TVR) of TA and GM muscles, and (4) the Hoffman reflex.

During static exercise, "central" fatigue was diagnosed in 5/12 subjects whereas in the 7 others "peripheral" TA fatigue was deduced from the absence of response to twitch interpolation and the post-exercise decrease in twitch amplitude. The sustained foot inversion was associated with reduced median frequency in TA but not in PL and GM muscles. After static exercise, in all subjects both the mean plantar and rearfoot surfaces increased, indicating a foot eversion, the TVR amplitude decreased in TA but did not vary in GM, and the Hoffman reflex remained unchanged.

Whatever was the mechanism of fatigue during the maximal foot inversion task, the facilitating myotatic reflex was constantly altered in foot invertor muscles. This could explain the prevailing action of the antagonistic evertor muscles.

1. Introduction

In a previous study combining computerized baropodometry, electromyography and force measurements (Vie et al., 2012), we showed that a maximal incremental running exercise produced alterations of the foot posture during the post-exercise upright stance. It was characterized by an increase in both the mean plantar and rearfoot surfaces, indicating a foot eversion. During barefoot walking, some people also have a tendency toward a foot eversion (Cornwall and McPoil, 2009; Pierrynowski and Smith, 1996; Powell et al., 2011). Foot eversion has most often been reported after fatigue protocols consisting of repeated concentric/eccentric foot adduction (Ferber and Pohl, 2011). No study was performed to assess a foot eversion after a selective fatiguing task of foot invertor muscles.

In all the aforementioned studies, including ours, the reflex loops controlling the foot muscles were not explored. An altered reflex control of the foot muscles might occur after a fatiguing task and the changes in post-exercise stationary upright standing might also partly result from an imbalance of the facilitatory/inhibitory reflex loops controlling agonistic and antagonistic muscles. We have already reported, after a fatiguing static handgrip, an altered proprioceptive reflex loop of the forearm muscles explored by the tonic vibratory response (TVR) (Brerro-Saby et al., 2008).

The mechanisms of fatigue, i.e. the failure to sustain contractions during a static effort, are complex (Enoka and Stuart, 1992). Force failure results from a contractile fatigue, called "peripheral" fatigue, characterized by a reduced twitch response to direct electrical muscle stimulation. The force decline during sustained static effort is often preceded by a fall of the median frequency (MF) of the power spectrum density distribution of electromyograms (EMG), called "central" fatigue (Badier et al., 1993; Bigland-Ritchie et al., 1986; Coulange et al., 2006; Marsden et al., 1983). This indicates a reduced recruitment of high-frequency motor units and constitutes an adaptive response which delays the occurrence of force failure. Recording a superimposed electrically-induced contraction at the

* Correspondence to: UMR MD2, Faculty of Medicine, Aix-Marseille University, Bd. Pierre Dramard, 13916 cedex 20 Marseille, France. Tel.: +33 4 91 69 89 25; fax: +33 4 91 69 89 27.
E-mail address: yves.jammes@univ-amu.fr (Y. Jammes).

0021-9290/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2013.04.005

limit of endurance during voluntary contraction is used as an indicator of "central" fatigue (Dousset and Jammes, 2003; Enoka and Stuart, 1992). Human studies (Bigland-Ritchie et al., 1986; Garland and McComas, 1990; Woods et al., 1987) suggest that the reduced recruitment of high-frequency motor units during fatiguing efforts may be attributed to a reflex mechanism due to the activation of the groups III and IV muscle afferents by the muscle metabolites. Moreover, electrophysiological studies in animals have also shown that muscle fatigue and muscle acidosis depress the facilitating influences exerted by the muscle spindles (Darques and Jammes, 1997; Decherchi et al., 1998; Graham et al., 1986; Lagier-Tessonnier et al., 1993). This could be responsible for the TVR depression reported in the fatigued forearm muscles in humans (Brerro-Saby et al., 2008). The fatigue-induced reduction of facilitating messages could partly explain the changes in motor unit recruitment reported during fatiguing efforts. All the aforementioned human observations concern fatiguing tasks of the forearm or thigh muscles. No data were found in the literature on the mechanisms of fatigue of foot muscles and their consequences on the sensorimotor control.

The present study focused on the consequences of a sustained maximal static contraction of foot invertor muscles on upright standing, explored by a stationary baropodometric platform, and the reflex control of foot muscles (TVR response of the TA and the Hoffman reflex). We hypothesized that a reduced myotatic reflex in invertor muscles could facilitate the actions of evertor ones

2. Material and methods

2.1. Ethical approval

This research adheres to the principles of the latest revision of the *Declaration of Helsinki*. The procedures were carried out with the adequate understanding and written consent of the subjects and the protocol was approved by the Ethics Committee on Human Experimentation of our institution (CCPPRB).

2.2. Subjects

Twelve healthy female ($n=4$) and male ($n=8$) subjects participated to this study (mean age: 34 ± 6 yr; mean weight: 68 ± 7 kg). None were involved in an exercise training program. All had normal-arched feet.

2.3. Plantar surfaces and center of pressure (barycentre)

Barefoot subjects were standing in double limb stance. The computerized 530×600 mm^2 stationary baropodometric platform (WinPOD, Medicapteurs SA, Toulouse, France) consisted of 2304 resistive load cells and its sampling frequency was 100 images s^{-1}. We measured the mean plantar surface and the repartition of the anterior (forefoot) and posterior (rearfoot) surfaces. The software also allowed us to determine the location of the center of pressure with computation of the barycentre surface.

For all other measurements, the subject was comfortably seated on a chair.

2.4. Maximal foot inversion force (MIF)

The maximal foot inversion force (MIF) was measured under isometric conditions using a custom-built device (Fig. 1A) (Vie et al., in press). The subject was seated on a chair with the thighs firmly strapped down to impede the thigh and knee abduction and also the hip adduction. The right foot was securely fastened with non elastic Velcro straps applied on the foot plate of the dynamometer so that the ankle was in a neutral position. The foot plate was articulated around a horizontal axis allowing only inversion movements in the frontal plane. The external side of the articulated support was connected to a vertically positioned load cell (Scaime model ZF 100, AS Technologies, Langlade, France: linear from 0 to 1000 N) which measured the force produced by the foot inversion motion. MIF was recorded on the Noraxon (Fig. 1B). At each epoch, three 5-s maximal inversion maneuvers were executed to determine the maximal inversion force (MIF).

In order to execute a maximal static inversion sustained until exhaustion, visual feedback was given from the strain gauge display to keep the force level constant. The endurance time to fatigue (Tlim) was measured from the onset of the plateau contraction to the first 20% fall of the force signal.

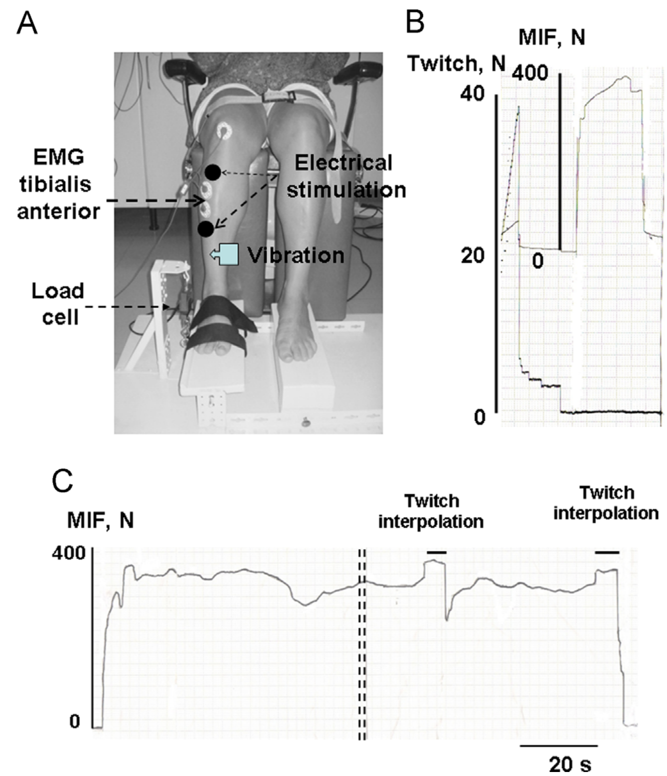

Fig. 1. (A) some of the tools used to explore the maximal static foot inversion with force measurement surface EMG recordings, electrical and vibration stimulations of *tibialis anterior* muscle; (B) pre-fatigue recordings of TA twitches and maximal inversion force (MIF); and (C) interpolation of TA twitches during the sustained foot inversion. Twitches and MIF are expressed in Newtons (N).

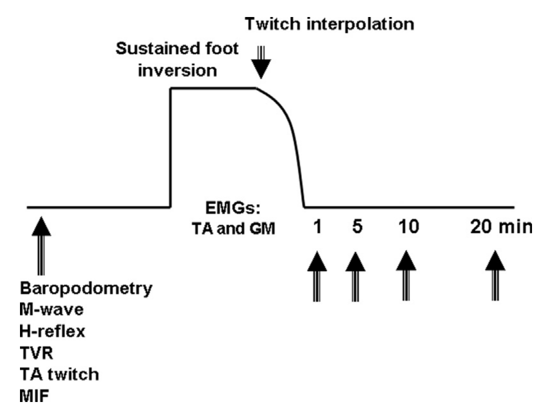

Fig. 2. Schematic representation of the protocol of static foot inversion with the instants of exploring maneuvers Baropodometry, M-wave and H reflex recordings, TVR recordings in *tibialis anterior* (TA) and *gastrocnemius medialis* (GM) muscles, production of TA twitches, and measurements of 5-s maximal inversion force (MIF). The arrow indicates the instant of TA twitch interpolation during the sustained static effort where surface TA and GM EMGs were continuously recorded.

2.5. EMG recordings and analyses during sustained efforts

Bipolar (30 mm center-to-center) Ag–AgCl surface electrodes (Dantec, 13L 20) were used to measure EMG voltage from the right TA, PL, and GM muscles, which respectively control the foot inversion, foot eversion, and plantar flexion. The electrodes were placed between the motor point and the proximal tendon. The inter-electrode distance was always 3 cm and the impedance was kept below 2000 Ω by careful skin shaving and abrasion with an ether pad. The EMG signal was recorded (Myosystem 1400A Noraxon Inc., Scottsdale, Arizona, USA), amplified with a common mode rejection ratio = 90 dB, input impedance = 100 mΩ, gain = 5000, the frequency band ranging from 10 to 10,000 Hz. The software program allowed us to calculate the power spectrum and the EMG signal was digitized with a sampling frequency of 2000 Hz using the data acquisition card mounted in the computer. For each contraction, an averaged power spectrum was obtained from