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Research article

Fatigue-induced decline in low-frequency common input to bilateral and unilateral plantar flexors during quiet standing

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ABSTRACT

Plantar flexor muscles play a crucial role in maintaining balance during quiet standing. The purpose of this study was to investigate the effect of their fatigue on common input to these muscles, using a coherence analysis. Thirteen healthy young male adults stood quietly before and after a fatigue protocol consisting of a heel raise exercise. Center of pressure (COP) displacement and electromyograms (EMGs) from the bilateral medial gastrocnemius and soleus muscles were recorded. EMG-EMG coherences between the bilateral homologous muscles (bilateral coherence) and within the unilateral muscles (unilateral coherence) in the right leg were calculated. Anteroposterior and mediolateral COP speeds, mediolateral COP SD, and 95% confidence ellipse area were larger in post- than pre-fatigue condition. Bilateral and unilateral coherences in delta band, that reflect comodulation of muscle activation, and bilateral coherence in alpha band, that is supposedly associated with the subcortical inputs, were smaller in post- than pre-fatigue condition. Unilateral coherences in alpha and beta band, reflecting physiological tremor and corticospinal drive, respectively, were not different between pre- and post-fatigue conditions. It is suggested that the low-frequency common input to the plantar flexor muscles is reduced following the fatiguing contraction during quiet standing, likely by a change in the postural control strategy.

1. Introduction

Balance maintenance is a fundamental requirement of many daily activities. The control of posture is accomplished by integrating sensory information from the visual, vestibular, and somatosensory systems and appropriately activating the postural muscles. During quiet standing, as the center of body's mass falls anterior to the ankle joint [36], the plantar flexor muscles play a primary role in keeping the upright posture [21]. It has been reported that low-frequency (< 5 Hz) common input to motor units in the bilateral soleus (SL) muscles and within the SL muscle is stronger during standing than voluntary isometric contraction [28].

One way to analyze the common input to muscles is a coherence analysis of surface electromyographic (EMG) recordings. It quantifies the common input to motor neuron pools [16] and has been used to investigate correlated activity of the plantar flexor muscles during standing tasks [7,31,35]. For instance, several studies have revealed coherences between the bilateral homologous plantar flexor muscles (bilateral coherence) and within the unilateral plantar flexor muscles (unilateral coherence) in delta band during quiet standing [7,31,35]. The coherence in this frequency band could reflect synchronous oscillations in motor unit firing rates (also known as "common drive") and thus comodulation of muscle activation [22]. Also, the bilateral coherence was observed in alpha band [7], though results have been inconsistent [31]. Given its origin being proposed to be the reticulospinal pathway projecting bilaterally [7], the bilateral coherence in alpha band may also reflect the comodulation of bilateral muscle activation. The other possible source of alpha-band oscillation could be the physiological tremor [24], but the tremor has been shown not to synchronize between bilateral hands [23], and thus is associated more with the unilateral alpha-band coherence [15]. In addition, beta-band coherence between synergistic muscles, reflecting the corticospinal drive [10], has been demonstrated to increase when difficulty of postural task increases [34,35].

One of the factors that can influence the postural stability is muscle fatigue [3,4]. It is defined as a decreased ability of muscles to produce

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forces and can occur through central (i.e., factors within the central nervous system) and/or peripheral (i.e., factors distal to neuromuscular junction) processes [14]. During as well as immediately following a submaximal fatiguing contraction, the delta- and beta-band coherences have been reported to increase [8,11,26], likely as a consequence of an increase in the excitatory drive to motor neurons to compensate for a decrease in motor unit force. Also, several studies have demonstrated an increase in the alpha-band coherence during the fatiguing contraction [11,19]. However, these studies were conducted in a single-joint movement or in hand muscles, and it is currently unclear how the common input to postural muscles are influenced by the fatigue during standing. Accordingly, we compared in this study the common input to the plantar flexor muscles during quiet standing between pre- and post-fatigue conditions, using the coherence analysis of surface EMG recordings. We hypothesized that the bilateral delta- and alpha-band coherences, and the unilateral delta-, alpha-, and beta-band coherences would be larger in post- than pre-fatigue condition.

2. Material and methods

2.1. Subjects

Thirteen healthy young male adults (mean age ± SD = 22.2 ± 0.73 years old, mean height ± SD = 170.2 ± 5.7 cm) participated in this study. We recruited only male adults because they exhibit less resistance to muscle fatigue [17]. None of the subjects reported any neurological, orthopedic, psychiatric, or cognitive disorders that could influence the postural control, or were under medication. All of them had normal or corrected-to-normal vision. The experimental protocol was approved by the ethics committee of Nagoya University, and the subjects gave a written informed consent before their participation.

2.2. Procedure

The subjects were asked to stand on a force plate quietly for 40 s with their bare feet parallel to each other (heel-to-heel distance of 15 cm) and their arms along the sides while looking at a fixation sign which was set 1 m in front of them. The feet positions were marked and kept constant during the whole experiment. The task was performed before and immediately after (< 10 s) a fatigue protocol.

The fatigue protocol consisted of a heel raise exercise. The subjects raised their heels until exhaustion (at least 3 min), and the protocol was ended when they were unable to raise their heels to the height that we measured at the beginning of the protocol, even with the verbal reinforcement. They were allowed to lightly touch a table during the heel raise exercise.

2.3. Data acquisition

Force signals were collected at 1000 Hz from a force plate (Tec Gihan, Kyoto, Japan) using a customized LabVIEW program (National Instruments, Austin, TX, USA). Surface EMG signals were recorded using wireless sensors (Trigno Wireless System, DELSYS, Boston, MA, USA). They were placed on the bilateral medial gastrocnemius (MG) and SL muscles, according to the SENIAM recommendations (http://www.seniam.org/), after the subject's skin was gently abrased and cleaned with alcohol. The EMG signals were amplified and band-pass filtered at 20–450 Hz using a bio-amplifier (Trigno Wireless System, DELSYS, Boston, MA, USA), and sampled at 2000 Hz.

2.4. Data analysis

A customized Matlab script (MathWorks, Natick, MA, USA) was used to analyze the data for the middle 30 s of the collection period. After calculating center of pressure (COP) from the force signals, we low-pass filtered the COP data at 15 Hz with a fourth-order zero phase lag Butterworth filter. The SD and mean speed of anteroposterior and mediolateral COP displacements and 95% confidence ellipse area were then calculated to evaluate the effect of fatigue protocol on the postural control.

The coherence analysis quantifies the strength of common oscillation between two signals and has been used to examine the common input to two different motor neuron pools. Initially, we rectified the EMG signals, as EMG rectification has been reported to enhance the firing rate information of motor unit pools [16,29,30]. We then calculated the auto-spectra of rectified EMG signals x and y (P_{xx} and P_{yy}), and the cross-spectra of the same signals (P_{xy}) with a discrete Fourier transform of non-overlapping segments, each consisting 1024 data points. The coherence ($|C_{xy}(f)|^2$) was then estimated using the following equation [16]:

$$|C_{xy}(f)|^2 = \frac{|P_{xy}(f)|^2}{P_{xx}(f)\bullet P_{yy}(f)},$$

where f is the frequency. The coherence was evaluated for the following muscle pairs: right MG and left MG (MG-MG), right SL and left SL (SL-SL), and right MG and right SL (MG-SL). The significant coherence was identified with 95% confidence limit.

To visualize the average difference between pre- and post-fatigue conditions, we also calculated the pooled coherence using the following equation:

$$C_{pooled} = \left| \frac{\sum_{i=1}^{k} L_i C_{xy}^i(f)}{\sum_{i=1}^{k} L_i} \right|^2,$$

where C_{xy}^i is the coherence at the frequency f from individual subject, L_i is the number of segments, and k is the number of subjects.

2.5. Statistical analysis

The COP parameters were compared between pre- and post-fatigue conditions using a paired t-test. The Wilcoxon signed-rank test was used when the assumption of normal distribution was violated. Similar to previous studies [7,31,35], we calculated z-transformed coherence and averaged it over the frequency ranges of 0–5 Hz (delta band) and 5–15 Hz (alpha band). We additionally averaged the z-transformed coherence over 15–35 Hz (beta band) only for the unilateral coherence, as the corticospinal tract predominantly projects contralaterally, and the beta-band coherence is not typically observed between bilateral muscles. The effects of time (pre/post) and muscle pairs (MG-MG/SL-SL) on the bilateral coherence were analyzed with a two-way repeated measure analysis of variance (ANOVA). The unilateral coherence (MG-SL) was compared between pre- and post-fatigue conditions using a paired t-test. No data were missing for all variables, and all statistical analyses were performed with SPSS (IBM, Armonk, NY, USA) with the significant level of 0.05.

3. Results

3.1. COP parameters

Results of the COP parameters are presented in Fig. 1. The Wilcoxon signed-rank test revealed a significant difference in the speed ($p = 0.001$) but not in the SD ($p = 0.15$) of the anteroposterior COP displacement between pre- and post-fatigue conditions. A paired t-test demonstrated significant differences in both the SD ($p = 0.001$, $t = 4.14$) and speed ($p = 0.008$, $t = 3.17$) of the mediolateral COP displacement between pre- and post-fatigue conditions. The 95% confidence ellipse area was larger in post- than pre-fatigue condition (Wilcoxon signed-rank test: $p = 0.001$).