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Short communication

Effectiveness of a tongue-placed electrotactile biofeedback to improve ankle force sense following plantar-flexor muscles fatigue

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ABSTRACT

To assess the effectiveness of a tongue-placed electrotactile biofeedback system to improve ankle force sense following plantar-flexor muscles fatigue, 11 young healthy adults were asked to perform an isometric contra-lateral force ankle-matching task in two experimental conditions of No fatigue and Fatigue of the plantar-flexor muscles and two conditions of No biofeedback and Biofeedback. The underlying principle of the biofeedback consisted of supplying subjects with supplementary information about the force developed by the plantar-flexor muscles through electrical stimulation of the tongue. Measures of the overall accuracy and the variability of the force ankle-matching performances were determined using the absolute error and the variable error, respectively. Results showed that (1) the Fatigue condition yielded increased absolute and variable errors relative to the No fatigue condition in the No biofeedback condition, whereas (2) no significant difference between the two No fatigue and Fatigue conditions was observed in the Biofeedback condition. These results suggest that subjects were able to integrate augmented sensory information delivered through electrotactile stimulation of the tongue to suppress the adverse effect of plantar-flexor muscles fatigue on ankle force sense.

1. Introduction

Muscle fatigue, commonly associated with physical activities, is one factor that could affect the integrity of the neuromuscular system (e.g. [1]). When localized at the plantar-flexor muscles, fatigue has recently been shown to degrade sense of force at the ankle joint [2]. Impaired ankle sense could represent a challenge for the accurate performance of various functional activities of daily living (standing, initiating gait, walking or driving), and could contribute to accidental injuries or falls. One way to improve an individual's ability to ankle sense force when one of the sensory inputs becomes reduced and/or altered could be the use of a biofeedback system whose underlying principle consists of supplying the user with augmented information to supplement the reduced and/or altered natural sensory information. Among the available biofeedback systems, those designed to employ electrotactile stimulation of the tongue to provide augmented information have received growing interest (e.g. [3–6]). These biofeedback systems present indeed the advantage of freeing visual and auditory channels by using another unexploited sensory channel to convey information, that could provide a perspective for their application outside the laboratory framework and permit their use over long-time period in real-life environment [3]. The purpose of the present study was to assess the effectiveness of a tongue-placed electrotactile biofeedback system to improve sense of force at the ankle joint following plantar-flexor muscles fatigue.

2. Methods

2.1. Subjects

Eleven male young healthy adults (age = 22.1 ± 2.8 years) voluntarily participated in the experiment. They gave their informed consent to the experimental procedure as required by the Helsinki declaration (1964) and the local Ethics Committee. None of the subjects presented any history of injury (sprain, strain or fracture), surgery or pathology to either lower extremity that could affect their ability to perform the experiment.

2.2. Experimental procedure

Ankle force sense measurements were carried out as previously done by Vuillerme and Boisgontier [2]. Subjects were seated comfortably in a chair with their right and left foot put on a pressure mapping system (FSA Seat 32/63, Vista Medical Ltd.; sensing area: 350 mm × 350 mm = 122,500 mm^2; sensors number: 1024; sensors dimensions: 3.94 mm × 3.94 mm; space between sensors: 2.7 mm; 0.84 sensor/cm^2), allowing real-time acquisition of the magnitude of pressure and the computation of the force exerted on each left and right foot sole. The ankle and knee joints were locked in place at 10° of plantar-flexion and 110° of flexion, respectively. A handheld press-button allowed recording the matching. Signals from the pressure mapping system and the press-button were sampled at 10 Hz and 100 Hz (12 bit A/D conversion), respectively. Data were collected for 10 s. In

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addition, a panel was placed above the subject's legs to eliminate visual feedback. A target force level of 50 N was used for all subjects, irrespective of their individual physical capacity, to best simulate real situations (e.g., standing, walking, running, driving) [2]. Once the subjects had generated the required target force level (±5%) through isometric contractions of their left plantar-flexor muscles, they were asked to match the magnitude of this reference force through isometric contractions of their right plantar-flexor muscles. When they felt that they had reached the target force, they were asked to press the button held in their right hand, thereby registering the matched force. Subjects were given no feedback about the accuracy of their force matching and were not given any speed constraints other than the 10-s delay to perform one trial.

This isometric contra-lateral force ankle-matching task was executed under two experimental conditions of No biofeedback and Biofeedback. The No biofeedback condition served as a control condition. In the Biofeedback condition, subjects performed the task using a biofeedback system whose underlying principle consisted of supplying them with supplementary information about the force developed with their right matching plantar-flexor muscles relative to their left reference plantar-flexor muscles through a tongue-placed tactile output device generating electrotactile stimulation of the tongue. This so-called tongue display unit (TDU), initially introduced by Bach-y-Rita et al. [7], comprises a two-dimensional array (15 mm × 15 mm) of 36 electrotactile electrodes each with a 1.4 mm diameter, arranged in a 6 × 6 matrix positioned in close contact with the anterior–superior surface of the tongue [4,5]. Electrotactile stimuli were delivered to the front part of the tongue dorsum according to the following coding scheme (Fig. 1):

(1) no electrical stimulation when the force developed by the right matching plantar-flexor muscles was similar to the force developed by the left reference plantar-flexor muscles (±5%) (Fig. 1A);
(2) stimulation of either the posterior or anterior zone of the matrix (2 × 6 electrodes) (i.e., stimulation of rear and front portions of the tongue) depending on whether the force developed by the right matching plantar-flexor muscles was less than (Fig. 1B) or greater than (Fig. 1C) the force developed by the left reference plantar-flexor muscles, respectively.

Note that the TDU was inserted in the oral cavity all over the duration of the experiment (i.e., in two experimental conditions of No biofeedback and Biofeedback).

The two No biofeedback and Biofeedback conditions were executed the same day before (No fatigue condition) and immediately after a fatiguing procedure (Fatigue condition), similar to that recently used by Vuillerme et al. [8] and Vuillerme and Boisgontier [2], whose aim was to induce a muscular fatigue in the plantar-flexor muscles of the right leg until maximal exhaustion. Subjects were asked to perform toe-lifts with their right leg as many times as possible following the beat of a metronome (40 beats/min). Verbal encouragement was given to ensure that subjects worked maximally. The fatigue level was reached when subjects were no longer able to complete the exercise. Immediately after the cessation of exercise, the subjective exertion level was assessed through the Borg CR-10 scale [9]. Subjects rated their perceived fatigue in the plantar-flexor muscles between "very strong" and "extremely strong" (mean Borg ratings of 7.5 ± 1.0). To ensure that measurements in the Fatigue condition were obtained in a real fatigued state, i.e. to limit recovery effect, various rules were respected (e.g. [2,7]): (1) the fatiguing exercise

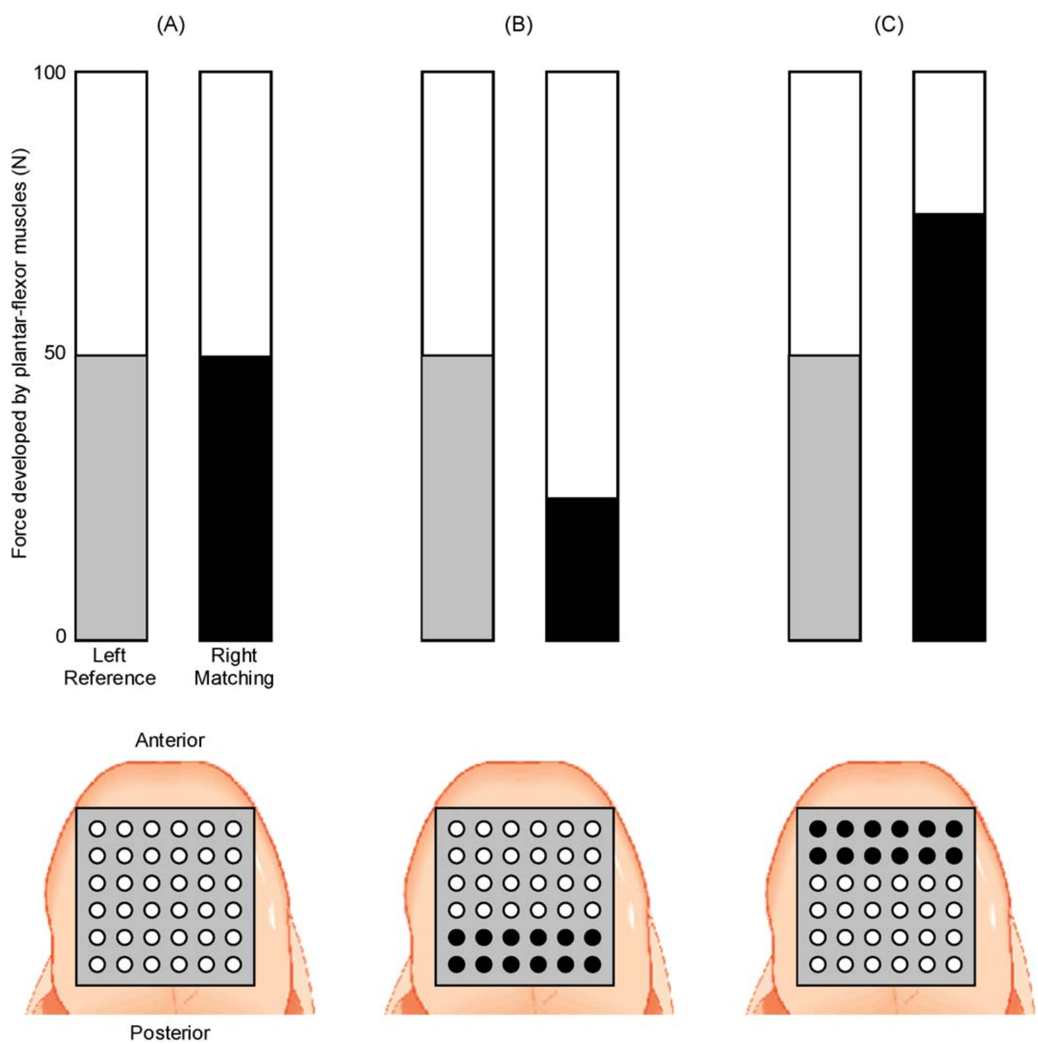

Fig. 1. Principle of the tongue-placed electrotactile biofeedback system. The three black and gray bars represent the force developed by the right matching plantar-flexor muscles and the left reference plantar-flexor muscles (upper panels). The three gray squares and the black dots represent the 6 × 6 matrix of electrotactile electrodes of the tongue display unit maintained in contact with the anterior–superior surface of the tongue, and the activated electrodes, respectively (lower panels). There were three possible stimulation patterns of the tongue display unit: (A) no electrical activation of any of the electrodes of the matrix when the force developed by the right matching plantar-flexor muscles was similar to the force developed by the left reference plantar-flexor muscles (±5%); (B) 12 electrodes (2 × 6) of the posterior zone of the matrix are activated (corresponding to the stimulation of the rear portion of the tongue dorsum) when the force developed by the right matching plantar-flexor muscles was less than the force developed by the left reference plantar-flexor muscles; (C) 12 electrodes (2 × 6) of the anterior zone of the matrix are activated (corresponding to the stimulation of the front portion of the tongue dorsum) when the force developed by the right matching plantar-flexor muscles was greater than the force developed by the left reference plantar-flexor muscles.

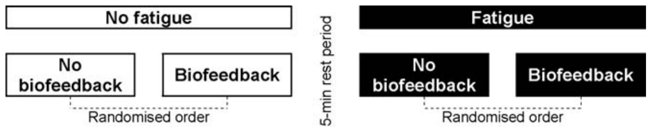

Fig. 2. Schematic representation of the experimental procedure used in the present study. Subjects were asked to perform an isometric contra-lateral force ankle-matching task in two conditions of No fatigue and Fatigue and two No biofeedback and Biofeedback. Each experimental condition consisted of five trials with a 5 s rest between trials. The order of presentation of the two No biofeedback and the Biofeedback conditions was randomised over subjects. The Fatigue condition was executed 5 min after the No fatigue condition.

took place beside the experimental set-up to minimise the time between the exercise-induced fatiguing activity and the measurements and (2) the duration of the data collection following the fatiguing exercise lasted approximately 1 min.

For each condition of No biofeedback and Biofeedback and each condition of No fatigue and Fatigue, subjects performed five trials, for a total of 20 trials. For each condition of No fatigue and Fatigue, the order of presentation of the two No biofeedback and Biofeedback conditions was randomised over subjects. The sketch of the entire experimental procedure is illustrated in Fig. 2.

2.3. Data analysis

Two dependent variables were used to assess force ankle-matching performances [10]:

(1) the absolute error (AE), the absolute value of the difference between the force developed by the right matching plantar-flexor muscles and the force developed by the left reference plantar-flexor muscles, as a measure of the overall accuracy of the force ankle-matching performances; and

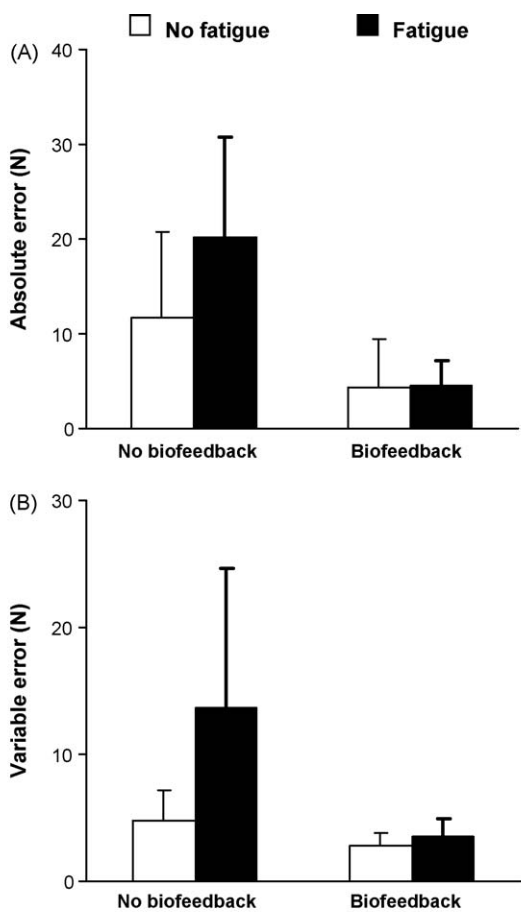

Fig. 3. Mean and standard deviation for the absolute error (A) and variable error (B) for two conditions of No biofeedback and Biofeedback and the two conditions of No fatigue and Fatigue. These two experimental conditions are presented with different symbols: No fatigue (*white bars*) and Fatigue (*black bars*).

(2) the variable error (VE), the variance around the mean constant error score, as a measure of the variability of the force ankle-matching performances.

Decreased AE and VE scores indicate increased accuracy and consistency of the force ankle-matching performances, respectively [10].

2.4. Statistical analysis

Data obtained for AE and VE were submitted to separate two Biofeedback states (No biofeedback *vs.* Biofeedback) × two Fatigue states (No fatigue *vs.* Fatigue) analyses of variances (ANOVAs) with repeated measures of both factors. Post hoc analyses (Newman–Keuls) were performed whenever necessary. Level of significance was set at 0.05.

3. Results

Analysis of the AE showed a significant interaction of Biofeedback × Fatigue ($F(1,10) = 11.64$, $P < 0.01$, Fig. 3A). The decomposition of the interaction into its simple main effects indicated that (1) fatigue increased AE in the absence of biofeedback ($P < 0.001$), whereas (2) AE was not affected by fatigue in the presence of biofeedback ($P > 0.05$). The ANOVA also showed main effects of Biofeedback ($F(1,10) = 19.78$, $P < 0.01$) and Fatigue ($F(1,10) = 5.52$, $P < 0.05$).

Analysis of the VE showed a significant interaction of Biofeedback × Fatigue ($F(1,10) = 5.46$, $P < 0.05$, Fig. 3B). The decomposition of the interaction into its simple main effects indicated that (1) fatigue increased VE in the absence of biofeedback ($P < 0.01$), whereas (2) AE was not affected by fatigue in the presence of biofeedback ($P > 0.05$). The ANOVA also showed main effects of Biofeedback ($F(1,10) = 12.20$, $P < 0.01$) and Fatigue ($F(1,10) = 8.66$, $P < 0.05$).

4. Discussion

Without the provision of biofeedback (No biofeedback condition), results showed less accurate and less consistent force ankle-matching performances in the Fatigue than No fatigue condition, as indicated by decreased AE and VE, respectively. In accordance with a recent report by Vuillerme and Boisgontier [2], these results confirm that muscle fatigue degrades force sense at the ankle joint. Conversely, when the biofeedback was available (Biofeedback condition), accuracy and consistency of the force ankle-matching performances were not affected by plantar-flexor muscles fatigue, as indicated by the significant interactions of Biofeedback × Fatigue observed for the AE (Fig. 3A) and VE (Fig. 3B), respectively. This result suggests that subjects were able to integrate augmented sensory information delivered through electrotactile stimulation of the tongue not only to improve ankle force sense, but also to suppress the adverse effect of plantar-flexor muscles fatigue. We could interpret these findings relative to the "sensory re-weighting" hypothesis (e.g. [11–14]) as follows. As a sensory input becomes lost or disrupted depending on the sensory contexts and the neuromuscular constraints acting on the individual, the central nervous system can selectively and adaptively "re-weight" the relative contributions of alternative available sensory inputs by increasing reliance on sensory modalities providing accurate and reliable information. Regarding (1) the alteration of proprioceptive information induced by the plantar-flexor muscle fatigue and (2) the augmented information provided by the biofeedback system, the present results are line in line with those of a recent study suggesting that the central nervous system was able to increase the relative contribution of the artificial tongue-placed tactile biofeedback to suppress the deleterious effect of plantar-flexor muscle fatigue on joint position sense at the ankle [8]. Generally speaking, although the experimental task was different, this interpretation also is consistent with the increased effectiveness of electrotactile tongue-placed biofeedback systems in improving balance control recently observed in sensory conditions of absent visual information [15], altered foot and ankle somatosensory information [6,16], and degraded vestibular and neck proprioceptive information [17,18]. Finally, even though the present study has been conducted in young healthy individuals, we believe that the present findings could have significant implications in the fields of orthopaedics and rehabilitation, for increasing/restoring the ability to sense force at the ankle. Along these lines, the effectiveness of the biofeedback system used in the present experiment is currently being evaluated in older adults and in individuals with functional ankle instability, known to exhibit ankle force sense deficits [19,20].

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Conflict of interest statement

There are no conflicts of interest.

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