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ORIGINAL ARTICLE

Changes in FDB and soleus muscle activity after a train of stimuli during upright stance

Alterações pós-trem de estímulo, na atividade dos músculos FDB e sóleus durante a postura ortostática

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Abstract

Background: Evidence of self-sustained muscle activation following a brief electrical stimulation has been reported in the literature for certain muscles. **Objectives:** This report shows that the foot muscle (*Flexor Digitorum Brevis* – FDB) shows a self-sustained increase in muscle activity during upright stance in some subjects following a train of stimuli to the tibial nerve. **Methods:** Healthy subjects were requested to stand upright and surface EMG electrodes were placed on the FDB, *Soleus* and *Tibialis Anterior* muscles. After background muscle activity (BGA) acquisition, a 50 Hz train of stimuli was applied to the tibial nerve at the popliteal fossa. The root mean square values (RMS) of the BGA and the post-stimulus muscle activation were computed. **Results:** There was a 13.8% average increase in the FDB muscle EMG amplitude with respect to BGA after the stimulation was turned off. The corresponding post-stimulus *Soleus* EMG activity decreased by an average of 9.2%. We hypothesize that the sustained contraction observed in the FDB following stimulus may be evidence of persistent inward currents (PIC) generated in FDB spinal motoneurons. The post-stimulus decrease in soleus activity may have occurred due to the action of inhibitory interneurons caused by the PICs, which were triggered by the stimulus train. **Conclusions:** These sustained post-stimulation changes in postural muscle activity, found in different levels in different subjects, may be part of a set of possible responses that contribute to overall postural control.

Keywords: physical therapy; posture; foot; human; electromyography; motor activity.

Resumo

Contextualização: Existem evidências de ativação autossustentada em certos músculos pós-estimulação elétrica. **Objetivos:** Mostrar que, em alguns sujeitos, o músculo do pé (*Flexor Digitorum Brevis* – FDB) também pode apresentar aumento de atividade autossustentada na posição ortostática pós-trem de estímulo no nervo tibial. **Métodos:** Sujeitos foram solicitados a permanecer na posição ortostática e sinais eletromiográficos foram coletados dos músculos FDB, sóleus e tibial anterior do membro inferior direito. Após a aquisição dos sinais eletromiográficos base (sem estimulação – BGA), um trem de estímulos de 50 Hz foi aplicado no nervo tibial (fossa poplítea). Foram analisados os valores RMS dos dados BGA e dos sinais coletados pós-estímulo. **Resultados:** Ao fim do estímulo, houve um aumento de 13,8% da atividade muscular do FDB em comparação com BGA. O mesmo fenômeno não aconteceu com o músculo sóleus, que apresentou uma diminuição de 9,2% da sua atividade pós-estímulo. Uma das hipóteses para a geração pós-estímulo da contração sustentada do FDB seria a da geração de corrente de entrada persistente (PIC) nos motoneurônios espinais do FDB. A diminuição da atividade do sóleus, pós-estímulo, pode ter ocorrido pela ação inibitória dos interneurônios causada pelos PICs gerados pelo trem de estímulo. **Conclusões:** Essas alterações das atividades sustentadas dos músculos posturais, pós-estímulo, encontradas em alguns sujeitos e em diferentes intensidades, podem fazer parte de um conjunto de possíveis respostas que contribuem para o controle postural.

Palavras-chave: fisioterapia; postura; pé; humano; eletromiografia; atividade motora.

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Introduction

The postural control system must be able to carry out at least three functions: to maintain the quiet stance posture against the force of gravity, to allow anticipatory responses to movements and to provide adaptations for optimized performance. All these features must include a sufficient and minimal number of muscles and have an organization that is reasonably independent from suprasegmental control[1]. The foot muscles are co-active with the leg muscles during many motor activities such as gait and posture. The flexor digitorum brevis (FDB) is a foot muscle that serves as a physiological extensor during quiet stance because its contraction acts against the force of gravity[2]. Some studies[3-8] have indicated that FDB activity is highly correlated with the position of the body's center of mass, suggesting that stabilization is among its functions. In addition, FDB activity is highly correlated with the soleus EMG pattern during upright posture, which may either be due to common descending commands that act on both MN pools or to common innervations of these pools by each muscle's afferents[3,5].

Motor neurons (MN) are the final link between the central nervous system (CNS) and the muscles and, hence, their properties affect how motor control operates. MN discharges control in a synergic way different muscles of the body and are essential for all movements and posture maintenance. A contraction is obtained when a train of electrical stimuli is applied directly to a muscle, but the muscle relaxes as the stimulation is turned off. However, when a stimulation train is applied to a nerve that innervates the muscle, a different phenomenon may occur: that of a sustained muscle contraction that outlasts the stimulus[9]. This can be associated with the activation of MN dendritic active channels in response to the spatio-temporal summation of excitatory postsynaptic potentials (EPSP), which causes a significant membrane depolarization that activates a persistent inward current (PIC). This PIC causes plateau potentials (PP) that lead neurons to discharge even after the input stimulus has been turned off, resulting in a so-called bistable behavior. The neuron may then be turned off by, for example, a hyperpolarization caused by inhibitory synapses[9-11]. Strong evidence for this phenomenon has been obtained from electrical stimulation of mixed nerves and from voluntary muscle activation in human MNs[9,11-16]. The PP phenomenon reduces the need for continuous synaptic input during muscle contraction, which may be useful in postural muscles, whose activity can be maintained without a continuous descending drive to keep the MNs firing[10,14,16]. Thus, a reduction in the energy required to maintain posture is possible, which would increase the system's efficiency.

Rehabilitation applications based on such phenomena include neurophysiological comprehension and the use of related electrical stimulation patterns as tools for postural muscle reeducation.

In spite of the intimate connection between the soleus and FDB muscles, the purpose of this study was to investigate the individual behaviors of the FDB and soleus after a stimulation train is applied during upright posture. Portions of these results have been previously presented as an abstract at a conference[17].

Methods

The experiments were carried out in eight healthy volunteers (yr, m and kg). All subjects gave informed consent and all procedures were approved by the Human Ethics Committee of the Institute of Psychology at the Universidade de São Paulo (USP), São Paulo, SP, Brazil (1705/CEPH-28/06/05).

Experimental apparatus and data analysis

The subjects were instructed to stay in an upright position. Each trial lasted 50 s, with the first 10 s disregarded to avoid possible adaptation periods and post-activation depression of reflexes[18]. The electromyograms (EMG) were recorded using surface electrodes (0.8 cm^2 Ag-AgCl) 2 cm apart, with the reference electrode attached distally. An electrolytic gel interface was placed between the skin and the electrode, which was then secured to the skin with micropore tape. Electrodes were attached at the following locations: the soleus (SOL) - distal to the end of the gastrocnemius muscles, the tibialis anterior (TA) - over the largest corresponding girth and at the FDB - over the plantar region of the foot, near the medial arch[16,19,20]. TA muscle activity was recorded to check for any occurrence of co-contraction or reciprocal inhibition. Prior to electrode attachment, the skin was abraded and cleansed with alcohol.

The EMG signals from the three muscles were amplified and bandpass-filtered (10-500 Hz) with a Nihon-Kohden MEB 4200 electromyography system before sampling at 5000 Hz. The signal acquisition, stimulus control and signal pre-processing were carried out with a DataWave system. The resulting files were then converted to ASCII and processed in MATLAB (Math Works, Inc).

A control EMG signal was acquired for an initial 20 s period. The following 20 s of data acquisition included an initial 2 s period when the tibial nerve was stimulated at the popliteal fossa by the Nihon-Kohden MEB 4200 machine. The stimulation consisted of a 50 Hz train of 1 ms pulses applied for 2 s[7].

To obtain a consistent H reflex, the subject was seated and the Sol muscle was relaxed. A minimal H reflex was considered when a consistent small H reflex was obtained for each stimulus pulse applied every 10 s. The stimulus pulse amplitude was set to 75% of the intensity required for a minimal soleus H reflex response to a single pulse. This value was smaller than what has been used in other studies[6,7,22] to avoid discomfort and to activate mainly large diameter sensory fibers. The sensation was perceived as an intense but painless vibration. The subjects did not know when the stimulus would be applied; they only knew that after being instructed to stand still the data acquisition would start and that they would subsequently receive the stimuli. No preparatory phase was observed in the EMG recordings of the three muscles.

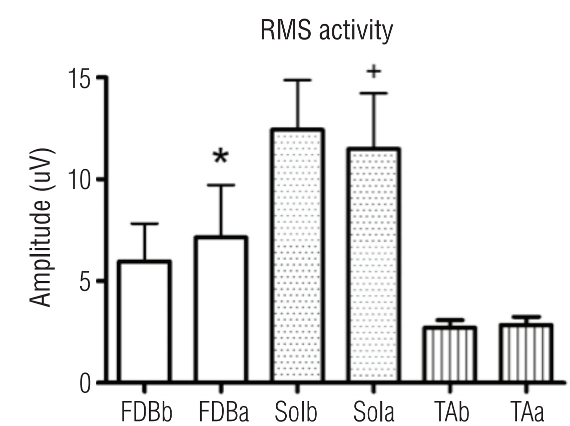
With the subject in the standing position, the electrical stimulation train evoked slight increases in soleus and FDB contractions (detected by palpation and observed, when feasible, as an increase in EMG intensity) without any visually noticeable ankle joint movement. The mean EMG values and a detailed visual analysis of the signals from the soleus and FDB muscles during the stimulus train indicated that no H reflexes were evoked in any subject at any time during the train. The TA and soleus EMGs had stimulus artifacts while the FDB EMG usually (but not always) was free of artifacts.

Each subject was submitted to three trials with eyes opened. The subject was instructed to ignore, as much as possible, the stimulation and remain in a comfortable upright posture. There were intervals of at least 1 min between the repetitions to avoid fatigue. The post-stimulation background muscle activity (BGA) and EMG signal were quantified by the root mean square value (RMS) of the EMG during the 20 s before the onset of stimulus train and for 18 s after the end of the stimulus train, respectively. The pre and post-stimulus RMS values obtained in the three trials for each subject were averaged. The data was submitted to Kolmogorov-Smirnov test for normality and used in the non parametric statistical analysis (Wilcoxon matched-pairs signed-ranks test, $p \leq 0.05$).

Results

The results for the studied subjects are synthesized in Figure 1. On average, FDB post-stimulus activity was higher than that of BGA, while soleus post-stimulus activity showed a tendency to be lower than that of BGA. The statistical analysis indicated a significant difference in FDB muscle activity (p=0.05), a tendency toward it for the soleus (p=0.09) and no difference for the TA.

The average pre- and post-stimulus EMG RMS measurements for each subject and their relative differences (in %) are shown in Table 1 for both muscles. Two subjects showed a strong increase in FDB (about 47%), while two others showed a mild increase (about 6%). Four of the subjects showed a medium decrease in soleus activity (20% on average). One subject (Subject 3) showed both effects at the same time; his raw data can be seen in Figure 2. Following the tibial nerve stimulus train, the subject's FDB EMG level was clearly higher than the pre-stimulus condition, while TA did not change and SOL decreased.



*p=0.05; +p=0.09.

Figure 1. Population averages of RMS values of the EMGs of the FDB, soleus and TA muscles before (FDB*b*, Sol*b* and TA*b*) and after the train of stimulation (FDB*a*, Sol*a* and TA*a*). The FDB activity increased in the average (p=0.05), the soleus activity showed a tendency to decrease (p=0.09) while the TA showed no change (p=0.2).

Table 1. Average RMS values for the FDB and Sol muscles before and after the stimulus train. The Percentage column represents a relation to the corresponding background muscle activity (BGA).

Subject	FDB before	FDB after	Percentage (%)	Sol before	Sol after	Percentage (%)	TA before	TA after	Percentage (%)
1	7.05	9.67	49.04	17.27	17.47	2.68	2.68	2.68	-0.0012
2	2.82	2.97	5.95	23.02	24.78	7.70	2.12	2.28	7.17
3	16.69	23.26	44.76	12.55	7.97	-35.55	2.00	1.97	-1.49
4	10.37	10.23	2.66	19.87	18.94	-5.23	4.73	4.78	1.05
5	1.63	1.74	6.60	4.92	4.89	-0.57	3.65	4.48	58.34
6	3.75	3.80	1.12	9.17	7.25	-12.55	1.93	1.87	-2.31
7	2.51	2.50	-0.56	5.30	4.25	-18.95	1.85	1.85	0.13
8	2.92	2.95	0.95	7.32	6.42	-11.54	2.78	2.77	0.03

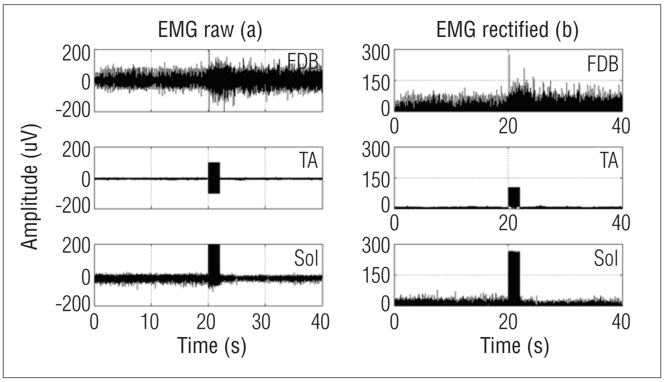


Figure 2. Raw (a) and rectified (b) EMGs of one of the subjects. From top to bottom: EMGs of FDB, TA and Soleus, respectively. The 50 Hz stimulation was turned on from 20 s to 22 s. The FDB showed a clear increase in EMG intensity during the 2 s train of stimuli. The TA and Soleus EMGs had a strong stimulus artifact occurring during the stimulus train which precluded an analysis of the level of soleus EMG during the stimulation period. After the stimulation was turned off the EMG level of the FDB increased and did not return to the control values, while that of the soleus decreased.

The observed changes in the post-stimulus EMG levels compared to BGA (either increased in the FDB or decreased in the soleus) did not return to baseline by the end of the 40 s signal acquisition period.

Discussion

The results for this studied sample indicated the existence of a sustained contraction of the FDB (innervated by a branch of the tibial nerve) after a train of stimuli was applied to the tibial nerve (at the popliteal fossa) with subjects in an upright position. Collins, Burke and Gandevia[14] sometimes found persistent post-stimulus activity in the TA muscle of seated subjects. Our data showed such an increase in half of the subjects: for two subjects it was strong and for other two it was mild. For the soleus, the opposite effect was seen in four of the subjects, i.e., a decreased (around 20%) post-stimulus EMG level compared to BGA.

Based on previous reports in the literature[13,15] the increases we found in post-stimulus FDB EMG activity may be attributed to the generation of persistent inward currents in the MNs driving that muscle. This behavior can be explained by neither the peripheral properties of nerve and muscle nor volitional drive to the motoneurons[13,14]. However, a plausible hypothesis is that the sustained muscle activity originated from the generation of persistent inward currents due to the temporal summation of excitatory post-synaptic potentials occurring at a high rate, such as the Ia terminals discharged following the stimulus train[9,13-15].

The subjects' responses ranged from little evidence of this behavior to large sustained activity following the stimulus train. This inter-subject variability may reflect individual differences in the thresholds for persistent inward current activation, perhaps due to different levels of neuromodulation in the spinal cord or to suboptimal stimulation frequency (50 Hz instead of 100 Hz as reported in the literature)[14,22]. Although the chosen stimulation level was lower than that used by other authors[13,15], which may also have limited its efficacy in triggering the PP mechanism, it assured on the other hand that mainly large diameter afferents were stimulated (e.g., Ia spindle afferents).

Surprisingly, in the standing position the soleus EMG levels of four subjects decreased after the stimulus ended, contrary to the increase described for seated subjects[9,11,13-16,22]. One possibility for this lack of increase in soleus activity is that while standing, the plateau potential mechanism would already be activated by the action of monoaminergic modulation[23]. On the other hand, in the sitting condition, which is associated with a lower level of arousal, no PICs would be generated in the MNs before application of the stimulus train, although during the train a strong depolarization of the MNs' membrane potentials would lead to the genesis of PICs. Whereas this could explain a lack of increase in soleus EMG activity, it cannot explain why the soleus activity in half of the subjects decreased after the stimulus train. Segmental and supra-segmental feedback loops that control the level of soleus torque to maintain balance could have activated inhibitory interneurons that synapse on the soleus MNs. The recent suggestion of the existence of persistent inward currents in spinal cord interneurons points to yet another possible source for decreased soleus activity: the genesis of persistent inward currents in inhibitory interneurons that act on the soleus MN pool[24], which are triggered by the sensory inflow caused by stimulation of the popliteal fossa. These potential inhibitory actions on the MN pool may also have turned off the persistent inward currents in a fraction of the soleus MN pool[25].

Another question is why the soleus motoneurons would exhibit plateau potential behavior in an upright posture while a postural synergist, the FDB muscle, would not. It may be that FDB MNs have higher thresholds for plateau generation or receive lower levels of neuromodulators than the soleus MN pool and thus are not under the influence of persistent inward current during quiet standing. Actually this hypothesis could justify broader research on the differences between FDB and soleus MN pools in humans, which, to the authors' knowledge has never been conducted; the relevance of such a comparison would stem from their synergies during posture. Different levels of change in post-stimulation activity of postural muscles were found in different subjects and may be part of a set of possible responses that contribute to overall postural control.

Horstmann and Dietz[26], described the importance of the availability and integrity of different sensory inputs (visual, vestibular and proprioceptive) to an effective postural control system. The feet have to be considered as a specific sensory-motor sub-system due to their importance for signaling the position of the body's center of gravity[27-29] and to muscles such as the FDB, which contribute to postural control[3-17,30]. That increased and sustained FDB activity can be triggered by appropriate stimuli reinforces the relevance of foot muscles for postural control. Moreover, a better understanding of the neurophysiology and mechanical effects of the FDB muscle may provide the conceptual tools necessary for improving and adapting clinical therapies for postural, ankle and foot rehabilitation. It is clear the results of this work would benefit from a larger sample. The importance of this work is to point to new and unexpected results regarding the leg and foot muscles when the tibial nerve was stimulated. These aspects deserve some attention. Previous work[22,31] trying to understand the central mechanisms behind electrical stimulation used small sample size.

The results described herein may represent an outline of the choices the nervous system has when activated by sensory inflow. Further work should be done with a larger sample and additional quantitative measurements such as joint kinematics and/or COP displacement. The results of this paper may be useful for interpreting future research that employs more natural stimuli, such as postural disturbances.

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