Facilitation of the soleus stretch reflex induced by electrical excitation of plantar cutaneous afferents located around the heel

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Abstract

Previous studies have demonstrated that plantar cutaneous afferents can adjust motoneuronal excitability, which may contribute significantly to the control of human posture and locomotion. However, the role of plantar cutaneous afferents with respect to their location specificity in modulating the mechanically induced stretch reflex still remains unclear. In the present study, it was hypothesized that electrical stimulation of the ipsilateral heel region of the foot is followed by a modulation of spinal excitability, leading to a facilitation of the soleus motor output. The study was performed to investigate the effect of excitation of plantar cutaneous afferents located around the heel on the soleus stretch reflex. The soleus stretch reflex was evoked by rotating the ankle joint in dorsiflexion direction at two different angular velocities of 50 and 200° s\(^{-1}\). A conditioning pulse train of non-noxious electrical stimulation was delivered to the plantar surface of the heel at different conditioning test intervals ranging from 5 to 100 ms. Excitation of plantar cutaneous afferents around the heel resulted in a pronounced facilitation of the soleus stretch reflex with magnitude and time course comparable for both velocities. This facilitation was manifested by a significant increase of reflex size for conditioning test intervals from 30 to 70 ms. The observed effect implies a potential functional role of cutaneous afferents in balance control conditions where the ankle is naturally disturbed, e.g., during step reactions to external perturbations.
Introduction

Considerable evidence has been brought forward, showing that plantar cutaneous afferents from the foot sole adjust motoneuronal excitability by modulating the level of both presynaptic and postsynaptic inhibition [13,25,26,28]. These findings strongly suggest that signals from cutaneous afferents of the foot sole interact with complex spinal interneuronal circuits associated with motor control and, therefore, contribute to the control of locomotion [8,9] and posture [24,27]. Moreover, it has been shown that electrical stimulation of cutaneous afferents innervating the foot results in complex excitatory and inhibitory reflex effects on a wide range of muscles acting about the ankle and knee [1,10,35]. During locomotion for example, cutaneous reflexes in the lower leg muscles in response to non-noxious electrical stimulation to the nerves innervating different areas of the foot are strongly modulated depending on the phase of walking and the nerve stimulated [2,32,35]. Recently, it has been demonstrated that electrical stimulation to different areas of the plantar foot results in differential effects on the motoneurons innervating the lower limb muscles: e.g., in soleus, an excitatory response was observed following stimulation of the heel region, which turned into an inhibitory response following stimulation of the metatarsal region [21,30,31]. Thus, it was concluded that the effects from cutaneous afferents in the plantar foot on the motoneurons innervating the lower leg muscles are based on mechanisms which are organized in a highly location-specific manner.

However, it is not widely explored to what extent stimulation of plantar cutaneous afferents modulates the excitability of a mechanically induced, i.e., a stretch reflex pathway. Due to the fact that, during balance control and the stance phase of locomotion,
the stretch reflex can resist a joint flexion produced by the resultant of the extrinsic forces (kinetic force and gravity) [15,23], the role of cutaneous afferents from the foot sole in modulation of stretch reflex excitability could be consequential.

The effect of conditioning plantar cutaneous stimulation on spinal reflex pathways was partially confirmed in previous studies. In this context, dissimilar but predominantly inhibitory modulation patterns of the motoneuronal excitability have been reported in studies with the H-reflex. Delwaide et al. have demonstrated that stimulation of the sural and saphenous nerves induces a bimodal excitation pattern in extensor motoneurons [7]. Other studies have reported a lack of change in the soleus H-reflex following excitation of cutaneous afferents of the foot sole and toes [25,28]. It was later proposed that conditioning stimulation of the common peroneal nerve resulted in presynaptic inhibition of the soleus H-reflex [13]. Lastly, Knikou studied the inhibition of the soleus H-reflex following the excitation of plantar cutaneous afferents and emphasized that signals from the cutaneous afferents of the foot sole interact with spinal inhibitory systems [16]. At the same time, it has been demonstrated that different mechanisms might be responsible for the modulation of the soleus H- and stretch reflex following a conditioning stimulation [20]. Furthermore, the dependence of the stretch reflex on the γ fusimotor drive activity, the involvement of more Ib afferents, weaker synchronization and larger duration of the afferent Ia volley, make an extrapolation of findings of the effect of plantar cutaneous stimulation on the H-reflex to a behavior of the stretch reflex unreliable.

As such, the present study was undertaken to clarify the role of plantar cutaneous afferents in modulating a mechanically induced reflex in the case of the soleus stretch reflex. Specifically, based on the aforementioned findings on the topographic
organization of cutaneous reflexes, the purpose of the present study was to investigate the effect of electrical stimulation of plantar cutaneous afferents located around the heel on the excitability of the soleus stretch reflex.
Methods

Subjects

Experiments were performed on twelve healthy subjects (eight male, four female) with an age between 23 and 36 years (Mean ± SD: 29.1 ± 3.0) and a height between 158 and 184 cm (173.4 ± 9.4). None of the subjects had any known history of neurological disorders. Each subject gave written informed consent to the experimental procedure, which was approved by the local ethics committee in accordance with the declaration of Helsinki on the use of human subjects in experiments.

Elicitation and recording of soleus stretch reflex

The participants were seated in an adjustable chair with the right foot firmly strapped to a foot plate. The positions of the hip and knee joints were set to 90 degrees of flexion, and that of the ankle joint to neutral position (0 degree dorsi-/plantar flexion). The axis of rotation of the ankle joint was aligned with the axis of rotation of the foot plate. Soleus stretch reflexes of the right leg were evoked by rotating the foot plate in dorsiflexion direction by a custom-made servo-controlled torque motor (Senoh Inc., Tokyo, Japan). Surface EMG signals were recorded by bipolar surface electrodes (Ag–AgCl, diameter 7 mm, Vitrode F, Nihon Kohden) placed longitudinally on the soleus muscle with an inter-electrode distance of 20 mm after cleansing and light mechanical exfoliation of the skin. The EMG signals were amplified 1000 times and band-pass filtered (15 Hz – 3 kHz) with a conventional bioamplifier (AB-651J, Nihon Kohden, Tokyo, Japan). The EMG data of the right soleus as well as the change in ankle angle of the right ankle joint were finally digitized at a sampling rate of 10 kHz.
The joint rotations were applied to the ankle joint at two different angular velocities of approximately 50 and 200° s\(^{-1}\). The two velocities, which were executed every 8 s in a pseudorandom order, led to joint rotations of 10° dorsiflexion. For each angular velocity and test condition, a minimum of ten soleus reflex responses were evoked.

*Conditioning stimulation of plantar cutaneous afferents*

The soleus stretch reflex was conditioned by non-noxious plantar skin stimulation delivered to the foot sole. Two self-adhesive, disposable surface electrodes (Vitrode W, Nihon Kohden) were placed over the surface of the right heel, which is innervated by the medial calcaneal branches of the tibial nerve. Specifically, the cathode was located over the medial side-surface of the heel and the anode laterally of the cathode over the stance-surface of the heel.

Using a constant voltage stimulator (DPS-1300D, Dia Medical System Co., Tokyo, Japan), the perceptual threshold (PT) that corresponded to the stimulus intensity first perceived by the subject was established. All conditioning stimuli were equivalent to three times PT. For pulse trains at this stimulation intensity, no movement of the intrinsic muscles of the foot was elicited and no pain reported, indicating that the conditioning volley excited mainly cutaneous afferents of the foot sole. These conditions also ensured that the stimulation intensity had no influence on the background EMG activity in the soleus during the resting condition (that is, without joint rotations). The conditioning pulse train, which consisted of five pulses (1 ms each) with an inter-stimulus interval of 3 ms, had a duration of 17 ms and preceded the onset of the ankle rotation at different conditioning test (C-T) intervals. With each angular velocity, the sets of constant C-T
intervals were delivered pseudorandomly, and ranged from 5 to 100 ms (5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 ms).

**Data processing**

The digitized EMG time series were full-wave rectified after subtraction of the DC component. The onset of the stretch reflex response was defined as the moment when the EMG activity reached levels higher than the mean EMG background activity plus two times its standard deviation. In accordance with previous studies [20,34], in the quiescent soleus only the short-latency component of the reflex, i.e., the M1 response was identified, which was analyzed by calculating the area under the curve of the full-wave rectified waveform. For the M1 duration of each subject, one of three constant intervals was used (25, 30 or 35 ms) that included the entire M1 response of that particular subject.

**Statistical analysis**

The M1 areas of the conditioned reflex responses recorded at each C-T interval were expressed as a percentage of the mean M1 area of the associated control reflex. Then, for each subject separately, a one-way analysis of variance (ANOVA) with a significance level of $\alpha = 0.05$ along with a subsequent Bonferroni test with a confidence interval of 95% was applied to the data to establish significant differences between the control and the conditioned reflexes. The mean sizes of the conditioned reflex from all subjects were then grouped based on the C-T interval investigated. Again, a one-way ANOVA ($\alpha = 0.05$ and $\alpha = 0.01$) along with a subsequent Bonferroni test (95 and 99%) was applied to the data to identify significant changes in the magnitude of the conditioned reflexes.
across the C-T intervals investigated. The results are presented as mean values and standard errors of the means (SEM).
Results

In Fig. 1, examples of the average soleus stretch reflex (n = 10) evoked at different angular velocities under control conditions and following excitation of the ipsilateral plantar cutaneous afferents are illustrated for one subject (C-T of 40 ms). The size of the stretch reflex responses increased proportionally with the rotation speed under both conditions. For both velocities, the conditioning stimulation of the plantar cutaneous afferents located around the heel delivered at 40 ms C-T intervals resulted in a marked facilitation of the soleus stretch reflex (Fig. 1). In ten of twelve subjects, the M1 response had a polyphasic shape, and in such cases, the changes of amplitude following excitation of the plantar cutaneous afferents were dissimilar: the most significant changes were observed in the first half of M1, that is, within the first 10 to 15 ms (Fig. 1). The second half of the M1 response did not display significant changes even in those trials where the facilitation of the soleus stretch reflex reached its maximal values – that is, when the duration of the C-T intervals resulted in a maximal facilitation of the soleus stretch reflex. Note that the described characteristics were true for all the ten subjects with polyphasic M1 responses.

In Fig. 2, the effect of plantar cutaneous afferent excitation delivered at different C-T intervals on the size of the soleus stretch reflex (M1) in the tested group is illustrated for each angular velocity. Note that the percentages are given with respect to the average control reflex. The C-T dependency of the reflex facilitation effect during conditioning cutaneous stimulation was consistently observed across all subjects and can easily be recognized in Fig. 2. The changes of the size of the soleus stretch reflex were quite prominent during the intermediate C-T intervals tested (20 to 70 ms). The magnitude of
the soleus stretch reflex facilitation was comparable for both angular velocities: the most significant reflex increase \((P < 0.01)\) corresponding to the 30 and 40 ms C-T intervals reached 145 ± 11% and 144 ± 10% \((50^\circ \text{s}^{-1})\), and 138 ± 5% and 137 ± 5% \((200^\circ \text{s}^{-1})\) of the control values, respectively. There was no conspicuous difference in the amount of the reflex facilitation during the conditioning stimulation delivered at short C-T intervals (5 and 10 ms). In this case, the size of the soleus stretch reflex varied around the control values, with some instances of being somewhat below them. Conditioning stimulation delivered at longer C-T intervals (80 to 100 ms) did not result in significant facilitation of the soleus stretch reflex, either. However, in most trials the conditioned reflex was slightly higher in comparison with the control values.
Discussion

Our experiment has revealed a pronounced facilitation of the soleus stretch reflex induced by stimulation of plantar cutaneous afferents located around the heel. This facilitation was manifested by a significant increase of reflex size for C-T intervals from 30 to 70 ms. The most considerable changes were observed within the first 10 to 15 ms of the M1 response, which could be attributed to the excitation of spinal motoneurons from the large diameter group Ia afferent fibers [19,33].

Two different angular velocities to evoke the soleus stretch reflex were used in the present study to evaluate the potential difference of the reflex modulation in the context of its possible functional contribution to motor control. However, we failed to recognize a prominent difference in the magnitude and time course of the reflex facilitation for the two angular velocities. Further research is necessary to investigate this issue in more detail.

The present work extends the reported findings with respect to the contribution of plantar cutaneous afferents within the spinal interneuronal reflex circuits. It has to be noted that our results seem to contradict numerous quantitative studies that indicated an inhibitory effect of plantar cutaneous afferents stimulation on the soleus motor output [11,16,18]. Goulart et al., for example, have revealed a strong inhibition of the soleus H-reflex during percutaneous electrical stimulation of the mixed posterior tibial nerve that preceded the elicitation of the reflex by 0 to 400 ms [11]. Additionally, Knikou has demonstrated that the excitation of plantar cutaneous afferents during C-T intervals ranging from 6 to 60 ms delivered to the metatarsal area, which is innervated by the medial plantar nerve, resulted in a significant inhibition of the soleus H-reflex [16]. On the contrary, our data has
revealed that stimulation of the plantar cutaneous afferents around the heel exerts a facilitation effect on the soleus stretch reflex. The differences in results, however, might be explained by the fact that the stimulation of the tibial nerve may produce compound reflex effects arising from different nerve branches, i.e., the lateral plantar, medial plantar, and calcaneal nerves. As such, all studies agree with previous findings that demonstrated the location-specific organization of the cutaneous reflexes in the plantar foot [21,30,31]. Nevertheless, in the study of Marque et al., stimulation of the same region as in the present study, i.e., the heel region innervated by the medial calcaneal branches of the tibial nerve, resulted in an inhibition of the soleus H-reflex [18]. The initial attempt to explain such significant difference between present results and those obtained by Marque et al. could be attributable to the methodological issue: in particular, it is necessary to clarify whether the intensity of cutaneous stimulation around the heel was comparable for the two studies. For instance, a number of authors have shown that a spinal reflex could be inhibited or facilitated depending on noxiousness that is due to the applied stimulus intensity [3,6]. In his paper, Marque et al. indicate that “the stimulus intensity was adjusted to imitate the sensation (around skin of the heel) evoked by tibialis nerve stimulation (0.8 x Motor Threshold)”, which was represented by a “weak local paraesthesia”. Although the stimulus intensity used in our study (equivalent to three times PT) could be considered higher, our subjects reported solely a short lenient tingling localized under the heel. Certainly, it is uneasy to collate subjective sensations, so we have to be careful when identifying differences in our results and those of Marque et al. However, since the stimulus intensity in both studies did not exceed a painful threshold, we suppose that the differences in intensity would not result in opposite effects on the
spinal reflex. At this point, we should consider the possibility of different mechanisms being responsible for the modulation of the soleus H- and stretch reflex following a conditioning stimulation. This difference has been demonstrated in the work of Morita et al. [20] and was explained by a different composition and/or temporal dispersion of the afferent volleys evoked by electrical and mechanical stimuli. Indeed, several previous studies have demonstrated that the soleus H-reflex is reduced in standing humans compared to that recorded in seated or prone human subjects [12,14,17], whereas the soleus stretch reflex was significantly facilitated during standing [22] and the stance phase of walking [5,29]. Certainly, this difference should be taken into account during the interpretation of our results.

Potential mechanisms that could be contributed to the facilitation of the soleus stretch reflex following the excitation of plantar cutaneous afferents include changes in the amount of both presynaptic and postsynaptic inhibition as well as segmental interneuronal effects [13,20,25]. The amazingly earlier onset of the stretch reflex facilitation (in the first half of M1 response) after conditioning might be in support of the presynaptic mechanisms [4,14]. On the other hand, as it follows from the study of Morita et al., the stretch reflex is more sensitive to postsynaptic inhibition and facilitation than to presynaptic one [20]. Thus, we cannot exclude a possible involvement of postsynaptic mechanisms. Nonetheless, in light of the current experimental protocol it is difficult to fully ascribe a differentiation between post- and presynaptic mechanisms.

However, the present results agree with the findings on the highly topographic nature of the cutaneous reflex modulation. As such, the contribution of the plantar cutaneous afferents in modulating the stretch reflex during the control of posture and locomotion
cannot be ignored as it may be functionally relevant for securing ankle joint stabilization
during perturbed upright standing or the stance phase of locomotion. Further research
with stimulation of more nerves or sole zones, as well as studies with different postural
conditions are planned to explicate the role of plantar cutaneous afferents in modulation
of the stretch reflex. Such a work may help to understand the fundamental mechanisms of
postural and locomotion control and may contribute to the development of novel methods
in rehabilitation and the detection of postural disorders that are due to aging.

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References


Figure Legends

Figure 1. The average soleus stretch reflex ($n = 10$) obtained from one subject under control conditions (black line) and during conditioning of the reflex at a C-T interval of 40 ms (gray line). Shown is the data recorded at angular velocities of (a) 50° s$^{-1}$ and (b) 200° s$^{-1}$. The vertical line indicates the time of onset of the foot plate rotation. The most prominent changes of the conditioned reflex occurred during the first half of M1 (square brackets).

Figure 2. Pool data showing the effect of plantar cutaneous afferent excitation on the soleus stretch reflex at angular velocities of (a) 50° s$^{-1}$ and (b) 200° s$^{-1}$. For each C-T interval tested, the overall average size of the conditioned soleus stretch reflex is presented (mean ± SEM). Asterisks indicate cases of statistically significant differences between the control and the conditioned reflex sizes (* $P < 0.05$; ** $P < 0.01$).