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Anticipatory Inhibition of EMG Activity of the Human *M. Soleus* at Voluntary Contraction of Its Antagonists

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Quantitative changes in background tonic EMG activity of *m. soleus* within a premotor period of voluntary contraction of its antagonists were examined in healthy humans. The above activity was recorded in the lying position at voluntary moderate tonic tension of this muscle and in the upright position, where the body was supported by both legs. The effect of voluntary flexion of the ipsilateral ankle joint (a simple motor reaction to a light signal) was examined. It was found that the intensity of *soleus* EMG in both tested positions, began to decrease 30–60 msec before the appearance of EMG activity recorded from the ankle flexor *m. tibialis anterior*, and such inhibition reached the maximum at the end of the premotor period. The observed dynamics of tonic EMG in the *m. soleus* show that an anticipatory drop in the activity of *soleus* motoneurons develops before the beginning of voluntary movements. Possible physiological mechanisms underlying this phenomenon are discussed. We believe that, within the premotor period, impulsation coming via mostly the corticospinal tract to *soleus* motoneurons decreases due to the action of central motor commands, and this leads to lowering of tonic tension of this muscle.

Keywords: electromyography, *m. soleus*, *m. tibialis anterior*, voluntary movement, premotor period, reciprocal inhibition.

INTRODUCTION

The interaction between flexors and extensors of the ankle joint during movements of the lower limb is one of the most studied manifestations of reciprocal relations in the CNS. This interaction plays an important role in posture maintenance and also in realization of various locomotor acts. The H reflexometry has been widely used in examination of reciprocal relations between muscle activity in humans, and the *m. soleus* served most frequently as the object for recording the H reflex. Several studies demonstrated that this reflex recorded from the *m. soleus* undergoes inhibition during voluntary flexion of the ankle joint [1–4]. Similar changes were found against the background of more complex movements where not only *soleus* antagonists but also other muscle groups were involved [5–7]. It was found that reciprocal inhibition of the H reflex is provided in this case by both postsynaptic and presynaptic inhibitory mechanisms [8–10].

Inhibition of the *soleus* H reflex is observed not only simultaneously with voluntary contractions of the antagonists of this muscle but also within the premotor period; this phenomenon develops several tens of milliseconds before the beginning of the respective motor event and is gradually intensified [8, 11, 12]. This anticipatory inhibition of the H reflex is one of the manifestations of the influence of central motor commands (CMCs) related to initiation of forthcoming voluntary movements. According to some data [8], this effect is based on disynaptic reciprocal Ia inhibition. However, other studies showed that intensification of depolarization of Ia afferent terminals in the *soleus* H reflex arc plays a leading role in the development of premotor inhibition of this reflex [11, 12]. This conclusion found some confirmations. Inhibition of the H reflex recorded from the *m. soleus* within the premotor period of a complex movement (transition of a tested subject from the sitting position to the upright one) was observed in the absence of alterations of motor responses of this muscle to transcranial magnetic stimulation of the neocortex [13].

Later on, it was found that, within the premotor period of voluntary flexion of the ankle joint, *soleus*

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motor responses to transcranial magnetic stimulation of the neocortex are intensified but not weakened simultaneously with inhibition of the H reflex [14]. This situation was explained by the removal of inhibition of propriospinal interneurons involved in the signal transfer along the cortico-spinal tract [15].

We examined anticipatory changes in the functional state of motoneurons of the *m. soleus* within the premotor period of contraction of its antagonists. The intensity of tonic *soleus* EMG activity was measured in these tests.

METHODS

The tests were carried out on 15 healthy adult subjects of both sexes. Each subject participated in one testing series.

We recorded EMG activity from the *m. soleus* and *m. tibialis anterior* using routine techniques; bipolar surface nonpolarizable electrodes (diameter 6 mm, interelectrode distance 15 mm) and an electromyograph, M-TEST (DX-Systems, Ukraine), were used. EMG potentials were amplified, filtered (range 10 to 1,000 Hz), digitized at a sampling rate of $2 \cdot 10^4$ sec^{-1}, stored on a PC hard disk, and subjected to off-line analysis.

Anticipatory changes in background EMG activity of the right *m. soleus*, which were related to voluntary flexion of the ipsilateral ankle joint, were examined. In the course of testing, the subjects were either in the upright position (the body was supported by both lower limbs) or in the lying position (the subjects lay on a couch, on the stomach, with the feet hanged down). In the latter case, the conditioning motor event was realized in the presence of voluntary tonic tension of the *triceps* muscle of the shin. In response to a light signal, the tested subjects performed voluntary flexion of the right ankle joint. This motion corresponded to a simple motor reaction. A light-emitting diode flash at a distance of 1 m from the subject served as the triggering signal. In the course of each trial, a warning signal was preliminarily presented, and, in 5 to 6 sec, a signal to perform the voluntary movement was applied. Prior to the experiment, the subjects were trained to perform the conditioning movement triggered by a light signal with a minimum latency.

The appearance of oscillations in EMGs recorded from the *m. tibialis ant.*, which significantly exceeded the level of the background activity, indicated the beginning of foot flexion. In the course of subsequent data processing, changes in the intensity of the EMG activity recorded from the *m. soleus* within the premotor period were quantitatively estimated using the electromyograph software. The recorded EMGs were full-wave rectified, and the integral area between the envelope curve and zero line was measured. A few pre-set intervals were selected for measurements of the intensity of EMG activity. These indices were normalized with respect to the control, i.e., the mean value of EMG activity recorded from the *m. soleus* before presentation of a light signal to initiate the conditioning movement.

In each test, 20 trials with about 30-sec-long intervals within the premotor period were performed; mean values of the intensity of EMG activity for such separate time intervals were calculated for each subject, and then for the entire experimental series. The statistical significance of differences among the measured values was estimated using the Wilcoxon *W*-test.

RESULTS

The intensity of background tonic EMG activity of the *m. soleus* noticeably decreased within the premotor period of flexion of the ipsilateral ankle joint. Such decreases became greater until the moment of appearance of EMG oscillations recorded from the anterior *m. tibialis ant.*

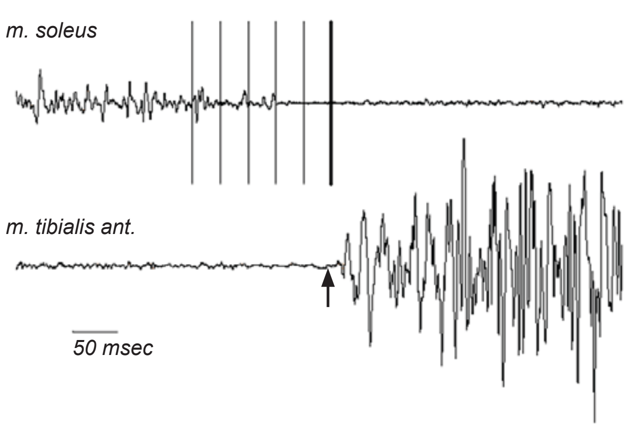
In the first series (eight testings), the subjects were in the lying position. After the warning signal, the subjects brought the ankle joint of the tested extremity into a state of extension and retained it in the state of moderate tonic tension of the shin *triceps* muscle. Upon the signal for beginning of the movement, the subjects performed rapid flexion of the ankle joint with subsequent return to the initial position. The latency of this movement in most trials was within a 0.2- to 0.3-sec range.

In Fig. 1, records obtained in a trial of this experimental series in one of the subjects are presented. As can be seen, the amplitude of oscillations of background tonic EMG recorded from the *m. soleus* began to decrease several tens of milliseconds before the appearance of EMG activity in the *m. tibialis anterior*; at the end of the premotor period, such activity was sharply suppressed. To obtain the quantitative characteristics of this process, the premotor period was divided in all trials into equal time intervals (30 msec each) in the reverse sequence from the moment of appearance of EMG in the *m. tibialis*. The intensity of integral EMG activity was measured in each of these intervals and normalized with respect to the control, i.e., to the value of EMG activity of the tested muscle 200 msec prior to presentation of the light signal. As can be seen, the intensity of this activity within the interval corresponding to 150 to 120 msec before the conditioning movement was equal to 90% of the control; within 120 to 90 msec, it was about 51%. Within 60 to 30 msec, the respective value dropped to 10%, and within 30 to 0 msec, this was only 5%.

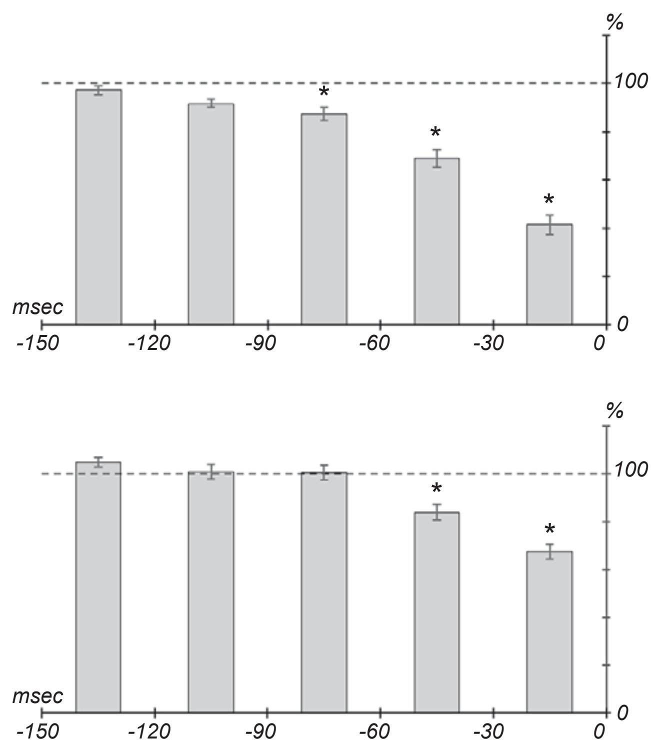
Figure 1 illustrates an intense suppression of EMG activity of the *m. soleus* leading to the development of a silent period was observed in a part of the trials of these series; this was observed. More frequently, clearly observable inhibition began to be manifested 60 to 30 msec before the beginning of the conditioning voluntary movement (ankle flexion), and the effect was weaker. Not the less changes in the mean indices of *soleus* EMG activity in all trials demonstrated a unidirectional pattern.

The average indices for the entire series are shown in Fig. 2A. The mean intensity of *soleus* EMG activity within 150 to 120 msec before the conditioning movement was equal to 97 ± 4% of the control. Within 120 to 90 msec, this was 92 ± 4%; within 90 to 60 msec, it was 87 ± 5%; within 60 to 30 msec, this index dropped to 64 ± 8%, and within 30 to 0 msec, it was equal, on average, to 41 ± 8%. A statistically significant drop in the intensity of *soleus* EMG activity began to be clear ($P < 0.05$) within the interval of 90 to 60 msec.

The second series was carried out in an analogous manner, but seven tested subjects were in the upright position, where the body was supported by both legs. In this case, the EMG activity of the *m. soleus* was sufficiently clearly expressed; naturally, there was no need to bring voluntarily this muscle into the state of tonic tension. During realization of a conditioning flexion of the right ankle joint, the subjects maintained a support on this lower limb on its heel. Results of this series also demonstrated the existence of anticipatory inhibition of *soleus* EMG activity (Fig. 2B). This effect was maximally expressed within the period directly preceding the conditioning voluntary movement. Under the above conditions, inhibition was, in general, weaker than in the above-described experimental series.



F i g. 1. EMGs recorded from the shin muscles (indicated above the traces) within a period preceding voluntary flexion of the ipsilateral ankle joint. Recordings were made when the tested subject was in the horizontal position. The appearance of *m. tibialis* EMG oscillations corresponding to the beginning of voluntary foot flexion is marked by an arrow. To measure the intensity of EMG activity recorded from the *m. soleus*, the premotor period has been divided into 30-msec-long intervals. Rectified and integrated EMG samples are not shown.



F i g. 2. Averaged normalized values of the intensity of the background EMG activity recorded from the *m. soleus* within different time intervals before contraction of the ipsilateral *m. tibialis anterior*. A and B) Recording of EMGs was performed in the lying position (8 tested subjects) and in the upright position (7 subjects), respectively. Abscissa) Time intervals, msec, measured within the premotor period with respect to the appearance of EMG oscillations in the *m. tibialis anterior* corresponding to voluntary flexion of the ipsilateral ankle joint; ordinate) mean values of the EMG intensity normalized with respect to the control values measured 200 msec before testing.

Averaging of the respective indices obtained in separate experiments showed that, in the examined group, noticeable (significant, $P < 0.05$) inhibition began from the interval of 60 to 30 msec, where the mean intensity of tonic *soleus* EMG was 84 ± 7%; within 30 to 0 msec, this index was 67 ± 7% of the control.

DISCUSSION

Our above-described own experiments showed that, at voluntary flexion of the foot, the integral intensity of tonic EMG recorded from the *m. soleus* (ankle extensor) decreases within the premotor period several tens of milliseconds prior to the beginning of the conditioning movement. This index is quantitatively linked with tonic tension of the tested muscle [16]. Relaxation of the *m. soleus* within the premotor period results from the anticipatory decrease in tonic activity of *soleus* motoneurons. This phenomenon corresponds to reciprocal relations between shin muscles, i.e., flexors and extensors of the ankle joint. It is obvious that this phenomenon developing within the premotor period cannot be of a reflex nature; it cannot be initiated by any signals coming from the periphery. Thus, it results from changes in the CMCs affecting the level of activation of *soleus* motoneurons. In this relation, two questions arise: (i) what is the pattern of these commands, and (ii) in what CNS structure are these commands generated?

As is known, tonic activity of motoneurons of ankle extensors in the upright posture is maintained, to a great extent, by the inflow of impulses from muscle receptors. The intensification of presynaptic inhibition of Ia afferents of the *m. soleus* observed within the premotor period of contraction of its antagonists [11, 12] provides limitation of this inflow and, correspondingly, induces a decrease in the activity of motoneurons of this muscle. Our tests showed, however, that such (and even greater) drop in the *soleus* EMG tonic activity can be also observed in the absence of loading in the feet, under conditions of voluntary tonic tension of the *m. soleus*. Thus, it looks probable that this phenomenon results from specific influences coming via descending pathways (mostly the cortico-spinal tract). As was found [17], presynaptic inhibition did not cover terminals of the cortico-spinal fibers.

As was repjrted [8], disynaptic Ia reciprocal inhibition of the *soleus* motoneurons is facilitated several tens of milliseconds before the beginning of voluntary flexion of the foot caused by stimulation of the *n. peroneus comunis*. Then it is intensified during the dynamic phase of contraction. It was found that interneurons of this inhibitory pathway can be activated not only by signals coming from the periphery but also by transcranial electrical [18] and magnetic [19] stimulation of the neocortex. Nonetheless, postsynaptic reciprocal Ia inhibition probably does not play a considerable role in the weakening of activity of *soleus* motoneurons within the premotor period. This assumption is in conflict with the data on intensification of motor responses of the *m. soleus* by transcranial stimulation of the neocortex within this period [14].

Based on these data, we believe that, during contraction of the antagonist of the *m. soleus*, the action of CMCs within the premotor period is realized to a great extent at the supraspinal level. This supposition has been confirmed by the recent data on morphological connections of neocortical neurons regulating the activity of flexors and extensors of the limbs and on the pattern of interactions among these neurons [20]. Due to intracortical neuronal connections in the motor cortex, a flexible control of contractions of antagonistic muscles may be realized. Such connections are also considered to be a structural basis for the formation of synergies and functional rearrangements in the cortex, which precede the initiation of voluntary movements [21]. As can be supposed, the processes occurring in the neocortex within the premotor period of contraction of the antagonistic muscles lead to weakening of impulsation coming via the cortico-spinal tract and addressed to motoneurons of the *soleus* muscle. The anticipatory decrease in tonic EMG activity of these muscles can result from the above-mentioned phenomena and events.

All tested subjects gave their preliminary written informed consent for their involvement in the experiments carried out in accordance with the regulations of the Helsinki Declaration. The performance of studies was approved by the Bioethics Committee of the Zaporizhzh`ya State Medical University.

The authors, É. I. Slivko, Ye. Z. Ivanchenko, G. R. Mikaelyan, and M. A. Panchenko, confirm that there had no conflicts of interest of any kind concerning commercial, financial or other relations in the course of the study and also those related to interactions between the co-authors.

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