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Auditory Stimuli to Study the Effects of Stimulation on Neural Oscillations

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***Abstract*—Although neural oscillations in the motor cortex in the beta (13-30 Hz) are prominent, their link to motor function is still largely unknown. To advance in the study of the role of these rhythms, it is relevant to find paradigms that can modulate them in a controlled way. Here we studied if transcutaneous spinal cord stimulation (tSCS) can entrain and drive cortical beta rhythms. To assess this, we used a paradigm based on auditory stimuli and tonic contractions to elicit beta oscillations recorded in the contracted muscles. Results show that auditory stimuli can reliably induce beta activity in muscles. These responses were then attenuated during periods of tSCS, which suggests that tSCS can interfere with beta activity in the motor nervous system.**

***Index Terms*—tSCS, HDsEMG, force, entrainment.**

I. Introduction

In the motor cortex, oscillations at different frequencies (e.g., beta and gamma) are prominent during different motor states and have been linked to different aspects of sensorimotor processing [1]. These cortical oscillations can modulate the activity in spinal motoneurons (MN), which are the last relay in the nervous system before behaviour. Thus, the electric fields produced by muscles may offer an indirect way to measure function-specific cortical oscillations [2].

To advance in the understanding of the roles and generation of neural rhythms in the motor cortex, it is useful to find methods that allow us to modulate this rhythmic activity. However, non-invasive techniques aimed at modulating brain oscillations have so far led to unclear evidence regarding their ability to change the activity in specific frequency bands. Recent studies provide evidence that spinal cord stimulation using modulatory signals may have a frequency-specific modulatory effect on neural rhythms that the brain transmits to the muscles [3]. This has so far been suggested for neural oscillations causing pathological tremors, but it may be also possible to modulate higher-frequency oscillations using similar procedures.

Here we tested whether transcutaneous spinal cord stimulation (tSCS) is able to interact with ongoing beta rhythms (around 20 Hz) that are transmitted between the motor cortex and contracted muscles. To do this, we used an experimental paradigm in which auditory stimuli were delivered to elicit transient increases in cortical beta activity [4]. This induced modulation in beta activity was assessed in intrinsic hand muscles during a pinching task so as to analyze how motor units were entrained by the beta information. This approach was used both during periods of tSCS at beta frequencies and at two control conditions, either not using stimulation or using a stimulus with a sub-optimal frequency (not matched with beta activity). This way we aimed at testing if tSCS can affect beta activity during motor states associated with different modulations in endogenous beta activity.

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II. Methods

Three human subjects, 1 left-handed, 2 males, mean age [± SD] 29 ± 9.5 years took part in the experiment. All procedures were approved by the Research Ethics Committee of the Community of Aragón (CEICA) and written informed consent from all subjects was obtained prior to the study.

Participants sat with their forearms resting on a table while grasping a support with their dominant hand (Fig. 1). They were asked to maintain a stable force at 15% their maximum voluntary contraction (MVC) (adjusted on a subject-by-subject basis, to ensure sufficient muscle activation and avoid fatigue), close their eyes, and listen to auditory stimuli ("beeps" of 50 ms at 1 KHz) through headphones, while receiving a) no stimulation, b) tSCS at the subject-specific beta frequency or c) tSCS at a sub-optimal beta frequency (explained below). For each condition, we conducted two blocks of recordings involving 20-30 auditory stimuli (approximately every 7±0.7 s).

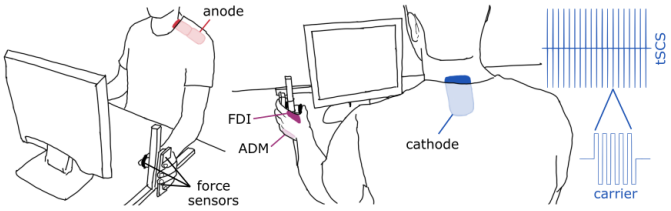

Fig. 1. Experimental set-up. The subject grasped a custom support with 3 force sensors. High-density surface electromyography matrices captured muscle activity from the first dorsal interosseuous (FDI) and the abductor digiti minimi (ADM). Auditory stimuli were delivered through headphones, and electrodes located over the clavicle and the spinal cord (C4-C7) delivered transcutaneous spinal cord stimulation (tSCS).

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Matrices of 96 electrodes with a 3 mm inter-electrode distance were fixed over the first dorsal interosseous (FDI) and the abductor digiti minimi (ADM), after skin preparation. HD-sEMG signals recorded from these matrices were band-pass filtered (10-500 Hz) and sampled at 2048 Hz (Quattrocento, OTBioelettronica, Italy). To analyze the HDsEMG signals in the time-frequency domain, all channels were averaged, rectified and detrended. For each trial, a sliding window (500 ms with a step of 10 ms) was used to estimate Welch's power spectral density (with a sub-window of 250 ms, without overlap). The power spectrum was averaged for all trials and normalized based on the mean pre-stimulus values. For further analyses, the muscle with the most prominent endogenous beta response to the auditory stimuli without tSCS was chosen.

One stimulation electrode (50x90 mm) was placed over the cervical region of the spinal cord (cathode) and two over the clavicle (anode), after skin preparation, to deliver tSCS pulses of 1 ms with high-frequency (5 KHz) carrier at 90% of the motor threshold (MT) (DS8R, Digitimer, UK). The MT was defined as the lowest stimulation intensity at which a consistent motor response was observed in at least 50% of the trials. The optimal beta frequency was estimated from the power spectrum of the HDsEMG after a first block of auditory stimuli without tSCS. The sub-optimal beta frequency was defined as 4 Hz below beta.

Force exerted (0-50 lbs) was measured by 3 compression load cells (FC22, Measurement Specialties, USA), sampled at 2000 Hz (Power1401, CED, UK), and displayed for visual feedback. First, subjects were instructed to grasp a platform producing their MVC in six repetitions. The minimum and maximum forces in each repetition were averaged and used to min-max scale the force input (adjusting forces to be in a scale of 0-100% of the MVC). To analyze force, a low-pass filter with a cut-off frequency of 20 Hz was applied, and the average from 1s before the stimulus to the stimulus was subtracted from the signals to remove the offset. Outliers were eliminated, and the mean and standard deviation were plotted.

III. Results

Auditory stimuli generated a small (below 0.05% change with respect to the target MVC) yet consistent response in force output featured by a brief drop in force, followed by a longer increase, which then returned to the initial levels. After this alteration, a pronounced activity ($+176\%$ maximum magnitude change with respect to pre-stimulus power spectrum) within the beta range (13-30 Hz) was shown by the time-frequency analysis of the HDsEMG signals (Fig. 2, top).

When the open-loop tSCS stimulation was applied at a beta or sub-beta frequency, the characteristic response at the force output was maintained, but the beta enhancement of the HDsEMG signals was generally lost (-65% and -79% compared to no stimulation trials, respectively).

IV. Discussion

Here we introduce an experimental paradigm allowing us to generate consistent cortical beta changes during muscle contractions to assess changes in the beta activity transmitted to muscles. This paradigm also allows the study of the effects of tSCS on the neural oscillations travelling along the motor nervous system. Our results suggest that beta increases induced by auditory stimuli are cancelled by tSCS.

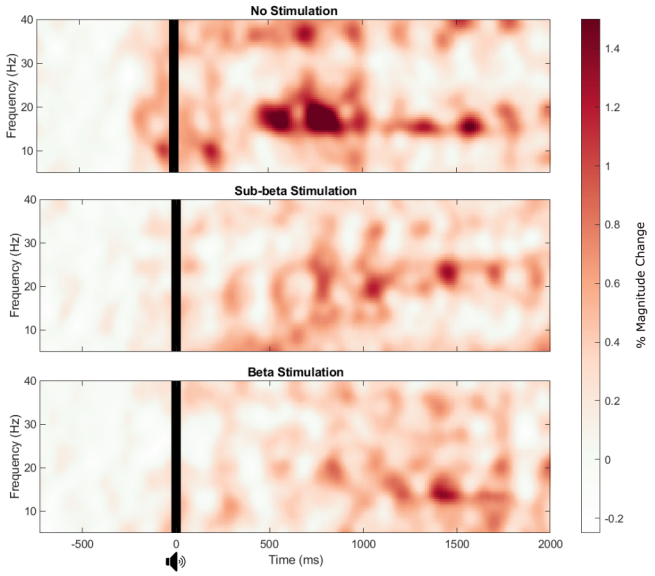

Fig. 2. Example time-frequency analysis of high-density surface electromyography signals from the first dorsal interosseous. The power spectrum from 1 s before the stimulus to the stimulus is used to normalize the remaining signal; change with respect to the pre-stimulus region is shown in the positive x-axis. A response in the beta frequency range can be observed when no tSCS is applied, which disappears when sub-beta or beta stimulation is delivered.

Because participants were asked to maintain a constant contraction throughout the session, auditory stimuli were not meant to withhold any motor command. Non-motor information, potentially processed at the cortex level, was passed down to the muscles within the beta frequency range. A slight change in force output, imperceptible by the subjects, was produced.

tSCS showed a clear effect on the beta activity of the HDsEMG elicited by the auditory stimuli.To delve deeper into the effects of the stimulation, an analysis of MN spike patterns will proceed. While the stimulation is subject to introduce noise into the recordings, the identification of MNs from the HDsEMG signals will allow the elimination of possible stimulation artefacts.

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