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Real-time changes in corticospinal excitability related to motor imagery of a force control task

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ABSTRACT

Objective: To investigate real-time excitability changes in corticospinal pathways related to motor imagery in a changing force control task, using transcranial magnetic stimulation (TMS).

Methods: Ten healthy volunteers learnt to control the contractile force of isometric right wrist dorsiflexion in order to track an on-screen sine wave form. Participants performed the trained task 40 times with actual muscle contraction in order to construct the motor image. They were then instructed to execute the task without actual muscle contraction, but by imagining contraction of the right wrist in dorsiflexion. Motor evoked potentials (MEPs), induced by TMS in the right extensor carpi radialis muscle (ECR) and flexor carpi radialis muscle (FCR), were measured during motor imagery. MEPs were induced at five time points: prior to imagery, during the gradual generation of the imaged wrist dorsiflexion (Increasing phase), the peak value of the sine wave, during the gradual reduction (Decreasing phase), and after completion of the task. The MEP ratio, as the ratio of imaged MEPs to resting-state, was compared between pre- and post-training at each time point.

Results: In the ECR muscle, the MEP ratio significantly increased during the Increasing phase and at the peak force of dorsiflexion imagery after training. Moreover, the MEP ratio was significantly greater in the Increasing phase than in the Decreasing phase. In the FCR, there were no significant consistent changes.

Conclusion: Corticospinal excitability during motor imagery in an isometric contraction task was modulated in relation to the phase of force control after image construction.

1. Introduction

Motor imagery is defined as the mental execution of an action without any physical movement or muscle activation [1]. Brain activity patterns during motor imagery are similar to those during the corresponding physical execution; the primary motor cortex (M1), premotor cortex, supplementary motor area, cerebellum, and basal ganglia are activated during motor imagery [2–7]. In addition, many studies have reported significant improvement of motor skills in patients with stroke as well as in healthy persons after motor imagery training [8–10]. Because force control is always needed to perform a motor activity, motor imagery training must somehow act on the neural substrates of force control. Thus, understanding the detailed effects of motor imagery on the neural substrates of force control is important for developing a

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better rehabilitative strategy involving motor imagery.

Transcranial magnetic stimulation (TMS) is a noninvasive method used to assess human corticospinal excitability. The increase in cortical excitability is evidenced by an increase in motor evoked potential (MEP) amplitude, and a reduction in the motor threshold of the stimulation [11,12]. Studies using TMS, which has good temporal resolution, have revealed increased corticospinal excitability during imagination of target muscle contraction without actual contraction [13–16]. Furthermore, Mizuguchi et al. [17] reported that changes in corticospinal excitability during such motor imagery were related to the imagined force level. Stinear and Byblow [18] noted that motor imagery of phasic thumb abduction temporally modulated excitability in M1, specific to the representation of the intrinsic hand muscle.

These previous studies have suggested that corticospinal excitability during motor imagery is modulated in a force level- and time-dependent manner. However, in many of these studies, the timing of the corticospinal excitability that was investigated using TMS was more closely related to the period during which tonic muscle contraction was imagined. In daily life, force control is finely tuned. Force needs to be increased or decreased with a high degree of control in order to accomplish a fine-motor task. To our knowledge, no study has yet attempted to examine how motor imagery changes corticospinal excitability during the increasing and decreasing phases of force control. We hypothesized that corticospinal excitability at such times would gradually increase or decrease, respectively, with the modulation of force. Such a finding would provide new insights into the mechanism underlying the real-time modulation of cerebral cortical activity according to the state of motor imagery. The aim of this study was therefore to examine the real-time changes in corticospinal excitability that occur during motor imagery in a task requiring isometric force control.

2. Material and methods

2.1. Participants

Ten healthy volunteers (three men and seven women, all right-handed, age range: 20–30 years, mean age: 22.7 ± 3.4 years) participated in the present study. None of the participants had any history of impairments in terms of neuromuscular or physical function that may have affected task performance. This study was performed in accordance with the tenets of the Declaration of Helsinki and was approved by the Local Ethics Committee of Kanagawa University of Human Services (Approval Number: HODAI 7–12). All participants provided written informed consent prior to their participation in the study.

2.2. Electromyography

Electromyography (EMG) of the right extensor carpi radialis (ECR) and right flexor carpi radialis (FCR) muscle was recorded using pairs of surface Ag/AgCl electrodes placed over these muscles in a belly − -tendon montage. The signal was amplified and filtered (band pass 5–3000 Hz) using a bioelectric amplifier (Neuropack MEB-2200; Nihon Kohden Corp., Tokyo, Japan), digitized at 4000 Hz, and stored for offline analysis on a laboratory computer (Power Lab system; AD Instruments Pty Ltd., New South Wales, Australia).

2.3. Experimental paradigm

The protocol adopted herein has been described in a previous study [19]. Briefly, the participants sat comfortably on a chair with their right forearms pronated at 45° and positioned horizontally over a table. Before initiating the experiment, we measured the force produced in wrist dorsiflexion when each subject performed maximum voluntary contraction (MVC) of the ECR against a plate that had a strain gauge (Kyowa Electronic Instruments Co., Tokyo, Japan) mounted to the vertical portion of the plate. The analog signal was amplified (SA-250 STRAIN AMPLIFIER; TEAC, Tokyo, Japan), filtered, and digitized (NI USB-6229 BNC; National Instruments Corp., Austin, TX).

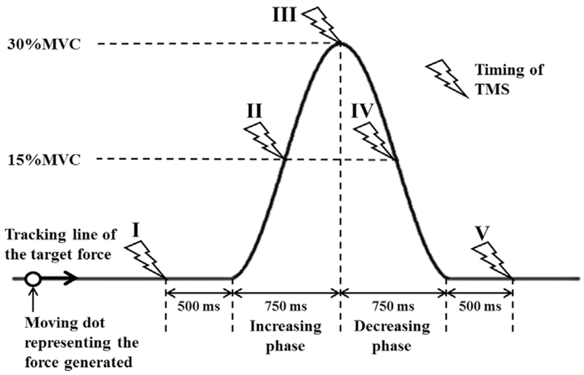

Fig. 1. Experimental design of a force tracking task.
Participants were instructed to adjust the isometric force of wrist joint dorsiflexion to keep a dot on a target tracking line on a monitor, while the dot moved from the left to right at a constant speed. During the performance test and the imagery test, no visual feedback was provided during tracking of the sine wave (fore generation phase). MVC; maximum voluntary contraction.

For the motor task, the participant was instructed to adjust the isometric force during right wrist dorsiflexion while watching a PC monitor that displayed a moving dot and a tracking line. The dot automatically moved horizontally from left to right at a constant speed (6 cm/s), but moved vertically according to the amount of dorsiflexion force exerted, such that the height of the dot was determined by the magnitude of the force generated. A force-tracking line was presented on the monitor as a sine wave with horizontal lines at both ends (see Fig. 1). The horizontal (flat) line indicated zero force. At the beginning of the task, the participants relaxed while the dot was moving from left to right on the horizontal line. Then, participants exerted (Increasing phase) and reduced (Decreasing phase) contractile force such that the dot was continuously maintained on the line of the sine wave; they then relaxed again (i.e., zero force) after the dot had passed over the sine wave. The peak of the wave, representing the target peak force during the task, was set at 30% of the wrist dorsiflexion MVC.

The experimental protocol is shown in Fig. 2. The experiment consisted of three sessions: the training session, which was used to construct the mental task image by motor learning and two test sessions, including the performance test and imagery test. In the training session, the participants repeatedly performed the motor task described above with actual muscle contraction in order to construct the motor imagery. Training consisted of four blocks, and each block was composed of 10 trials.

In the performance test, the participants performed the actual motor task without visual feedback; the target waveform and the dot disappeared at the time the contraction started. To describe the learning curve needed to guarantee imagery construction, a performance test consisting of 10 trials each was carried out at three time points: before training (pre-training), and after the second and fourth training blocks (post-training).

For the imagery test, the participants performed the task without physical muscle contraction, and with no visual feedback, as per the performance test. Participants were instructed to imagine using force control similar to that used during training. During imagery, it was confirmed that there was no muscle contraction by monitoring the EMG. The imagery tests, consisting of 50 trials each, were carried out before training and after the fourth training block (post-training). A custom-written computer program (LabVIEW software, ver.7.1; National Instruments Corp., Austin, TX) was used to design the experimental paradigm, including the TMS protocol described below.