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SENSORIMOTOR EVENT-RELATED DESYNCHRONIZATION REPRESENTS THE EXCITABILITY OF HUMAN SPINAL MOTONEURONS

M. TAKEMI, [a] **Y. MASAKADO,** [b] **M. LIU** [c] **AND J. USHIBA** [c,d]*

[a] *School of Fundamental Science and Technology, Graduate School of Science and Technology, Keio University, Kanagawa, Japan*

[b] *Department of Rehabilitation Medicine, Tokai University School of Medicine, Kanagawa, Japan*

[c] *Department of Rehabilitation Medicine, Keio University School of Medicine, Tokyo, Japan*

[d] *Department of Biosciences and Informatics, Faculty of Science and Technology, Keio University, Kanagawa, Japan*

Abstract—Amplitudes of mu and beta (7–26 Hz) oscillations measured by electroencephalography over the sensorimotor areas are suppressed during motor imagery as well as during voluntary movements. This phenomenon is referred to as event-related desynchronization (ERD) and is known to reflect motor cortical excitability. The increased motor cortical excitability associated with ERD during hand motor imagery would induce a descending cortical volley to spinal motoneurons, resulting in facilitation of spinal motoneuronal excitability. Therefore, in the present study, we tested the association of ERD during motor imagery with the excitability of spinal motoneurons in 15 healthy participants. Spinal excitability was tested using the F-wave recorded from the right abductor pollicis brevis muscle. The F-wave results from antidromic activation of spinal motoneurons and is induced by peripheral nerve stimulation. Participants performed 5 s of motor imagery of right thumb abduction following 7 s of rest. The right median nerve was stimulated at wrist level when the ERD magnitude of the contralateral hand sensorimotor area exceeded predetermined thresholds during motor imagery. The results showed ERD magnitude during hand motor imagery was associated with an increase in F-wave persistence, but not with the response average of F-wave amplitude or F-wave latency. These findings suggest that the ERD magnitude may be a biomarker representing increases in the excitability of both cortical and spinal levels.

Key words: electroencephalography, cortical oscillations, spinal excitability, F-wave, motor imagery.

*Correspondence to: J. Ushiba, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa, Japan. Tel/fax: +81-45-563-1141.
E-mail address: ushiba@brain.bio.keio.ac.jp (J. Ushiba).

Abbreviations: ANOVA, analysis of variance; APB, abductor pollicis brevis; CMAP, compound muscle action potential; EEG, electroencephalography; EMG, electromyography; ERD, event-related desynchronization; MEP, motor-evoked potential; TMS, transcranial magnetic stimulation.

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INTRODUCTION

Several distinct cortical circuits, such as the basal ganglia-thalamocortical and prefrontal-supplementary motor area circuits, contribute to voluntary movements (Haggard, 2008). These circuits converge on the primary motor cortex (M1), which conveys motor commands to spinal motoneurons and muscles. Cortical activity accompanying voluntary movements is often investigated by electroencephalography (EEG), in which waveforms reflect the electric activity of cortical neurons.

One example of a motor-related EEG component is a power decrease in mu and beta (7–26 Hz) oscillations that are time-locked to an event. This phenomenon is referred to as event-related desynchronization (ERD) and is considered to represent increased activation of the corresponding cortical area (Pfurtscheller and Lopes da Silva, 1999). ERD is observed over the contralateral primary sensorimotor area (SM1) during motor imagery as well as during actual movement (Miller et al., 2010; Yuan et al., 2010).

The results of previous studies suggest that ERD is a biomarker representing the corticospinal excitability. For example, motor-evoked potential (MEP) induced by single-pulse transcranial magnetic stimulation (TMS) is larger in a condition accompanying alpha band ERD compared with a condition without the ERD (Hummel et al., 2002). Additionally, Schulz et al. (2013) reported a correlation between a decrease in beta band EEG power related to motor preparation and an increase in MEP amplitude. A negative correlation between MEP amplitude and sensorimotor EEG power in either the alpha (Sauseng et al., 2009) or beta band (Mäki and Ilmoniemi, 2010) was also found at rest. However, it remains unclear whether the independent excitability of spinal motoneurons is associated with ERD magnitude. Furthermore, while various studies have reported different functional roles of alpha and beta rhythms (McFarland et al., 2000; Hansen and Nielsen, 2004; Hari, 2006; Brinkman et al., 2014), previous findings on the correlation between EEG power and MEP amplitude suggest ERD frequency band representing the spinal excitability is possible at either the alpha or beta band.

Voluntary relaxation depresses spinal motoneurons, whereas motor imagery without overt muscle contraction counters this effect (Taniguchi et al., 2008; Ichikawa et al., 2009; Hara et al., 2010; Fujisawa et al., 2011). Mercuri et al. (1996) demonstrated a transient facilitation of spinal motoneurons by subthreshold TMS to the M1. Long-term potentiation-like plasticity in the M1, induced

by subthreshold 5-Hz repetitive TMS, increases spinal excitability (Quartarone et al., 2005). These studies inferred that the increase of motor cortical excitability without overt muscle contractions (e.g., motor imagery involving ERD) is likely to facilitate spinal motoneurons. Nevertheless, no empirical evidence is available concerning the correlation between motor-related EEG components and spinal motoneuronal excitability.

The purpose of the present study was to examine the association between ERD in EEG and the excitability of spinal motoneurons during hand motor imagery. We used a small (<0.5 mV) orthodromically evoked compound muscle action potential (CMAP) known as a F-wave, as a measure of the excitability of spinal motoneurons (Espiritu et al., 2003; Lin and Floeter, 2004). Spinal excitability can be examined by both H-reflex and F-wave. They are both elicited by peripheral nerve stimulation, but the physiological mechanisms underlying these stimulus-evoked responses are not equivalent. The F-wave results from antidromic activation of spinal motoneurons (Mercuri et al., 1996) and solely depends on the excitability of spinal motoneurons, whereas the H-reflex can be altered by the excitability of spinal motoneurons as well as mechanisms acting on the afferent volley (Pierrot-Deseilligny and Burke, 2005). Typical F-wave measurements assessing spinal excitability are mean amplitude and frequency of occurrence. To measure the frequency of F-wave occurrence at a fixed ERD magnitude, peripheral nerve stimulation was triggered by a predetermined ERD magnitude, which was calculated from online EEG, and the F-wave measurements between three different ERD magnitudes were compared. Considering the trough of EEG oscillations reflecting action potentials in cortical cells (Creutzfeldt et al., 1966), it is plausible that in addition to the ERD, the EEG phase has an effect on the spinal excitability. Therefore, the effect of oscillation phases on F-wave occurrence was also examined.

EXPERIMENTAL PROCEDURES

Participants

Fifteen healthy participants (aged 22.1 ± 1.7 years; 12 men, 3 women) joined this study. All were right-handed, without any medical or psychological disorders, and had normal vision (according to self-reports). All participants were initially naïve to the experiment. The purpose and experimental procedure were explained to the participants and written informed consent was obtained. The study was approved by the local ethics committee of the Keio University and performed in accordance with the Declaration of Helsinki.

Data acquisition

EEG was recorded with 29 g.LADYbird active electrodes in g.GAMMA cap[2] (g.tec medical engineering GmbH, Graz, Austria). Electrodes were placed at Fp1, Fp2, F7, F3, Fz, F4, F8, FC3, FCz, FC4, T7, C5, C3, C1, Cz, C2, C4, C6, T8, CP3, CPz, CP4, P7, P3, Pz, P4, P8, O1, and O2, as designated according to the International 10–20 System. The ground electrode was located on the forehead, and the reference electrodes mounted on both right and left earlobes. EEG signals were band-pass filtered (0.1–100 Hz with 4th order Butterworth) with a notch (50 Hz for avoiding power line contamination) and digitized at 512 Hz using a biosignal amplifier (g.USBamp; g.tec medical engineering GmbH).

The F-wave was recorded from the right abductor pollicis brevis (APB) muscle using bipolar Ag/AgCl electrodes (φ = 10 mm). The cathode was placed over the belly of the APB muscle, and the anode was placed over the tendon near the metacarpophalangeal joint of the thumb. Impedance for all channels was maintained below 20 kΩ throughout the experiment. F-wave signals were band-pass filtered (20 Hz–2 kHz with 2nd order Butterworth), digitized at 10 kHz using a biosignal amplifier (Neuropack MEB-9200; Nihon Kohden, Tokyo, Japan), and monitored throughout the experiment.

To elicit F-waves, the stimulating electrodes consisted of the cathode, which was placed over the right median nerve 3 cm proximal to the palmar crease of the wrist joint, and the anode, which was 2 cm proximal to the cathode (Fujisawa et al., 2011). The maximal stimulus was determined by delivering 0.2-ms square-wave pulses with increasing intensity to elicit the largest M-wave. The M-wave is a large (>5 mV) orthodromically evoked CMAP observed prior to the F-wave, that results from the direct excitation of motor axons. Supramaximal shocks, 20% higher than the maximal stimulus, were delivered for acquiring F-waves with the fixed repetitive time schema as described below (*Experimental protocol*). The recording of each F-wave began 50 ms prior to median nerve stimulation and ended after 100 ms.

Experimental protocol

Each participant took part in a series of four experimental sessions: Screening session and F-wave Conditions 1, 2, and 3. Initially, each participant engaged in the screening session. Following this, participants performed F-wave Conditions 1, 2, and 3, which were randomly determined so that the order was different for each participant. The screening session and F-wave Conditions 1, 2, and 3 were performed on the same day.

In the screening session (Fig. 1a, top row), the participant sat in a comfortable armchair and placed their palm upward on the armrest. A 24-inch computer monitor was placed 1 m in front of the participant's eyes. The screening session consisted of 30 trials. Each trial started with the presentation of the word "Rest" at the center of the monitor. Six seconds later, the word "Ready" was presented for 1 s. The monitor then displayed the word "Execution" and the participant performed sustained thumb abduction for 5 s. After a short pause, the monitor displayed the word "Rest," and the next trial began.

In F-wave Condition 1 (Fig. 1a, middle row), we applied suprathreshold electrical stimulation to the right median nerve at the wrist level during the rest condition.