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Influence of motor imagination on cortical activation during functional electrical stimulation

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HIGHLIGHTS

- In a motor imagery based BCI system to control FES, practicing imagery both before and during FES additionally increases intensity of event related desynchronisation throughout the whole period of electrical stimulation.
- Discontinuing to practice motor imagery following the onset of FES, reduces subsequent event-related desynchronisation.
- Motor imagery and FES produce event-related desynchronisation in similar frequency ranges.

ABSTRACT

Objective: Motor imagination (MI) and functional electrical stimulation (FES) can activate the sensory-motor cortex through efferent and afferent pathways respectively. Motor imagination can be used as a control strategy to activate FES through a brain–computer interface as the part of a rehabilitation therapy. It is believed that precise timing between the onset of MI and FES is important for strengthening the cortico-spinal pathways but it is not known whether prolonged MI during FES influences cortical response.
Methods: Electroencephalogram was measured in ten able-bodied participants using MI strategy to control FES through a BCI system. Event related synchronisation/desynchronisation (ERS/ERD) over the sensory-motor cortex was analysed and compared in three paradigms: MI before FES, MI before and during FES and FES alone activated automatically.
Results: MI practiced both before and during FES produced strongest ERD. When MI only preceded FES it resulted in a weaker beta ERD during FES than when FES was activated automatically. Following termination of FES, beta ERD returns to the baseline level within 0.5 s while alpha ERD took longer than 1 s.
Conclusions: When MI and FES are combined for rehabilitation purposes it is recommended that MI is practiced throughout FES activation period.
Significance: The study is relevant for neurorehabilitation of movement.

1. Introduction

The adult brain is capable of adapting to environmental challenges, such as learning new skills, and to functional disabilities produced by a lesion to the nervous system (Celnik and Cohen, 2004). In able-bodied individuals activity dependant neuroplasticity is driven by a voluntary activation of the cortex resulting in activation of muscles in conjunction with feedback from sensory receptors activated by that movement. The existence of these adaptation processes stimulated the development of neurorehabilitation interventions geared to enhance neuroplasticity when it plays a beneficial role and to inhibit it when it is detrimental (Celnik and Cohen, 2004). Neuroplasticity generally manifests as an increase in the excitability of corticospinal circuits which over time strengthens the connectivity of the cortico-spinal pathways. This strengthening is associated with improved motor learning (McDonnell and Ridding, 2006), improved motor function

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following stroke (Powell et al., 1999; Conforto et al., 2002), spinal cord injury (Hoffmann and Field-Fotte, 2007) and other central nervous system damages (Everaert et al., 2010; Stein et al., 2013).

In recent years Brain Computer Interface (BCI) has been proposed as a tool for promoting neurorehabilitation of motor functions in patients with stroke and spinal cord injury (Dobkin, 2007; Grosse-Wentrup et al., 2011; Keiser et al., 2014). Typically a BCI control strategy is motor imagination (MI) which is a mental simulation of an action (Jeannerod, 2001; Mulder, 2007). BCI can be used to control a functional electrical stimulator (FES) applied to the patient's upper or lower limb muscles (Tam et al., 2011; Dally et al., 2009; Vuckovic et al., 2014) while the patient performs MI of the limb's movement. Such a setup is called BCI controlled FES, or simply, BCI–FES. The purpose of MI is dual: to provide a BCI command signal to control FES and to activate the efferent motor pathways. The purpose of FES is to activate the afferent pathways. It is believed that MI timely preceding the FES can induce activity dependant plasticity in patients incapable of performing an overt (executed) movement (Dobkin, 2007; Keiser et al., 2014). A study on able-bodied participants by Mratchacz et al. (2012) demonstrated that a timely combination of MI and FES is crucial for the strengthening of Cortico-Spinal (CS) pathways. They measured cortical evoked potential during MI and delivered FES at different phases of MI. A subsequent motor evoked potential was maximal when FES was delivered during maximum negative phase of movement-related cortical potentials.

Although it is believed that the precise timing between the onset of MI and FES is important for strengthening the CS pathways (Mratchacz et al., 2012), it is not known whether a prolonged MI during FES affects the cortical activity induced by FES. In stroke patients and patients with incomplete SCI, MI produces stronger activation of the sensory-motor cortex than FES (Szameitat et al., 2012). Therefore a sustained motor imagery during FES might result in a stronger and more sustained activation of the sensory-motor cortex. Yet BCI–FES studies typically do not specify to participants whether or not to continue with MI once they activate the FES. Motor imagery is a cognitively demanding condition (Jannerod, 2001; Mulder, 2007), therefore most BCI users would probably stop performing MI once they activate FES, unless told otherwise.

Multiple EEG studies compared brain activation during different modalities of covert and overt movements: imagination of movement, observation of movement, passive movement and movement caused by electrical stimulation. Alegre et al. (2002) analysed event related synchronisation/desynchronisation (ERS/ERD) (Pfurtscheller and Lopes da silva, 1999) during passive movements and found beta ERD during the passive movements and post-movement beta ERS. Cho et al. (2011) compared EEG patterns during active movements, passive robotic movements, MI, FES producing only sensation and FES producing sensation and muscle contraction. They found similar ERS/ERD patterns in the lower beta range for all modalities except for MI of movement. Müller et al. (2003) showed that a major time–frequency difference between active and FES induced movements was the presence of ERD prior to movement onset in the active case. Although multiple EEG studies compared ERS/ERD patterns of MI and FES, these two modalities have typically been analysed separately. Therefore there is no study looking into the influence of MI on FES, which is important to consider should these two modalities be used together.

A study by Saito et al. (2013) demonstrated that electrical stimulation with intensity above the motor threshold, delivered during prolonged repetitive MI, increases the excitability of the corticospinal tract. While MI in that study was not used to control the electrical stimulator, the study supports the idea of practicing MI during FES. On the other hand, studies on repetitive or sustained movements (Cassim et al., 2000; Erbil and Ungan, 2007) showed that prolonged movements do not necessarily produce prolonged ERD throughout the whole movement. Therefore, it is possible that the contribution of ERD induced by prolonged MI during FES is very small.

In this study we used MI based BCI to compare ERS/ERD responses based on three covert movements paradigms: MI before FES, MI before and during FES and FES alone activated automatically. We show that continuing MI during FES produces the strongest ERD over the sensory-motor cortex. When MI preceded FES, but was not practiced during the FES, it resulted in weaker beta ERD during FES than when FES was applied on its own. The results are relevant for designing neurorehabilitation therapies which combine synchronous activation of sensory and motor pathways.

2. Methods

2.1. Participants and procedures

Ten able-bodied volunteers (ages 27 ± 5, 5F, 5M) participated in the study. Ethical permission was obtained from the College of Science and Engineering Ethical Committee. All participants signed an informed consent form.

2.2. EEG recording

The EEG was recorded using the gtec EEG amplifier (Guger Technologies, Austria). A ground electrode was attached to participants' left ear. EEG was recorded bipolarly from the electrodes located at CF3-CP3, CFz-CPz and CF4-CP4. Because analysis was performed only for the right hand in this study, CF3-CP3 and CF4-CP4 will be referred to as the contralateral and ipsilateral side respectively. The location CFz-CPz will be referred to as the central area. The sampling frequency was 256 samples/s and the EEG signal was filtered between 5 and 60 Hz using 5th order Butterworth filter within the g-Usbamp device, set through a graphical user interface. Impedance was kept under 5 kΩ.

2.3. Experimental protocol

The experiment comprised two parts, an off-line and an on-line study. In the first, off-line study, participants were asked to perform cue-based MI of their left and right hand and these data were used to build a BCI classifier. In the on-line study part, the classifier built during the off-line part was used to implement a BCI controlled with MI of only the right hand waving movement.

2.3.1. Off-line cue-based BCI classifier

An experimental protocol that instructed participants to imagine left and right hand movements was devised using visual cues. Participants were seated at a desk, approximately 1.5 m in front of a computer monitor. Participants were instructed to look at the centre of the monitor and were instructed to respond to a sequence of visual cues. At $t = 0$ s a readiness cue (a cross +), which remained on for 4 s, appeared on the computer monitor. At $t = 1$ s an initiation cue, presented as an arrow, was displayed for 1.25 s, pointing to the left (←) or to the right (→). The left and right arrows corresponded to the left and right hand kinaesthetic MI of waving respectively. Participants were asked to continue with MI until the cross disappeared from the screen (3 s after the initiation cue appeared). Although later analysis will be performed only for MI of the right hand, an experimental paradigm with MI of both hands was chosen to assure that motor preparation did not start following the readiness cue (a cross). In total there were 40 trials comprising 20 trials for the left and 20 trials for the right hand MI