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Cortical Activation Pattern for Grasping during Observation, Imagery, Execution, FES, and Observation-FES integrated BCI : An fNIRS pilot study *

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Abstract— **Passive movement, action observation and motor imagery as well as motor execution have been suggested to facilitate the motor function of human brain. The purpose of this study is to investigate the cortical activation patterns of these four modes using a functional near-infrared spectroscopy (fNIRS) system. Seven healthy volunteers underwent optical brain imaging by fNIRS. Passive movements were provided by a functional electrical stimulation (FES). Results demonstrated that while all movement modes commonly activated premotor cortex, there were considerable differences between modes. The pattern of neural activation in motor execution was best resembled by passive movement, followed by motor imagery, and lastly by action observation. This result indicates that action observation may be the least preferred way to activate the sensorimotor cortices. Thus, in order to show the feasibility of motor facilitation by a brain computer interface (BCI) for an extreme case, we paradoxically adopted the observation as a control input of the BCI. An observation-FES integrated BCI activated sensorimotor system stronger than observation but slightly weaker than FES. This limitation should be overcome to utilize the observation-FES integrated BCI as an active motor training method.**

I. Introduction

Over the last decades, promising methods in neuro-muscular rehabilitation have been introduced based on the evidence of neural plasticity, which refers to the ability of the brain to change its structure and function by external stimuli [1]. Passive movement, action observation, and motor imagery have been suggested to manipulate external stimuli in order to facilitate motor function as motor execution as well [2, 3, 4].

Passive movement, i.e. the affected limb is passively moved by the therapist, a functional electrical stimulus (FES), or robot, could activate the sensorimotor system. FES and robots have been widely used to aid in improvement or to assist with functional activity of patients after brain injury such as post-stroke [5]. Because neurologic recovery of an injured brain itself is also important as much as functional recovery during early stage of rehabilitation after stroke, the principle of the neural plasticity could be necessary for passive movement controlled by FES or robots how to activate cortical system in view of motor facilitation.

Action observation which utilizes movement observation, and motor imagery, which utilizes the imagery of movements are increasingly attracting attention [3, 4]. Action observation method is that subjects watch video footage of a series of movements undertaken by another person during which the subject attempts to mentally simulate the same actions [3]. In contrast, motor imagery method has defined the repetitive mental practice of the internal replay of specific movements or actions [4]. Initial evidence suggests that movement observation or imagery can be applied in rehabilitation [6]. These methods do not require actual physical movement and are therefore beneficial for patients with motor paralysis. This is why they have been recently chosen as practical tools of neuromuscular rehabilitation using brain computer interface (BCI) [7, 8, 9].

The BCI is expanding in hopes of improving quality of life for people who are paralyzed or severely motor impaired [7]. In BCI, brain signals are analyzed in order to decode the subjects' mental state and map it onto some external action. Recently, BCI research outputs demonstrate a potential application in the neural rehabilitation of motor disabilities of patients who suffered stroke. BCI integrates the available rehabilitation tools including robot or FES in order to provide more natural and active therapy for efficient motor recovery [5]. When executing mental tasks such as observation and imagery, clarification of cortical activation patterns is most important to get the physiological understanding for utilizing them as the control input of BCI for neuromuscular rehabilitation.

The purpose of this study is to investigate the cortical activation patterns during execution, observation, imagery, and passive movements. In addition, this paper presents an example of BCI based active motor training which integrates the principle of action observation and passive movement by FES. We use an fNIRS to analyze the cortical activity. fNIRS is an emerging non-invasive brain sensing modality that allows for estimation of hemodynamics as an index of neural activation [10]. Oxy-hemoglobin (HbO) and total-hemoglobin (HbT), the most commonly used parameters of fNIRS, measure neural activity indirectly by detecting hemodynamic changes of the underlying cerebral cortex. The rationale for this estimation is based on the concept that neural activation in response to external stimuli results in increased energy demands in the activated area. When a specific area of the brain is activated, oxygen consumption concurrently increases by neuronal cells within the activated area. Consequently, an

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increasing change in HbO and HbT occurs during neural activation.

II. Materials and Methods

A. Participants

Seven healthy right-handed volunteers between 29 ~ 32 ages with no history of neurological, physical, or psychiatric illness participated in this study. All subjects understood the purpose of the study and gave written informed consent prior to participation.

B. Task and Procedure

Participants were seated on a chair in an upright position and they were asked not to move the trunk. We divided into two procedures according to the tasks. They participated in the execution, observation, and imagery of the actions of hand grasping and passive hand grasping by FES. Each trial was repeated five times by each subject. The protocol for each condition was as follows: rest (10 s), task (20 s), and rest (10 s). Task and rest were cued by beep sound at every start. In rest phase, all subjects were instructed to keep their eyes closed and to relax without performing any movements or any imaginations. The sequence of the trials for every subject was randomly assigned. During passive hand grasping by FES, four electrodes were patched on the skin of right arm at the region of flexor (two electrodes) and extensor (two electrodes) muscles to make flexion/extension movement of the right fingers (from second to fifth).

Four task conditions were presented in the trials: (1) For motor execution (*Execution*), volunteers were instructed to flex and extend their right hand with a frequency of 0.5 Hz paced by an auditory cue presented via digital metronome; (2) Under the observation condition (*Observation*), participants were instructed to watch a video clip showing a hand which moved in the same way as required by the Execution condition; (3) For motor imagery with the right hand grasping (*Imagery*), participants were instructed to purely imagine the same hand grasping as in Execution; (4) Under the passive movement condition (*FES*), participants were instructed to relax their hand and let it be moved freely. In particular, they were instructed not to help, aid, or support the movement. The participant's hand rested on the table, which was moved as flexion/extension by FES. All of task conditions were played with a frequency of 0.5 Hz.

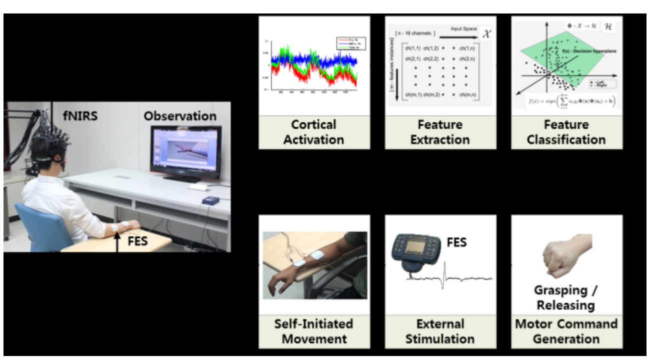


Figure 1. Self-controlled BCI paradigm integrating observation with FES

To test for BCI based active motor training, we analyzed the neural signals to extract the motor intention and decode it into external commands to activate the FES during action observation. From this procedure, subjects could perform the motor execution by their voluntary motor intention via self-controlled BCI paradigm (*BCI*). It can provide the sensorimotor loop as follows; external visual stimuli (*Observation*) – motor cortical activation – extracting motor intention – feeding it forward FES – external movement stimuli (*FES*) – visual feedback of real movement – Observation – continued to following modes repetitively during task. The test flow was depicted in Fig. 1.

C. fNIRS Procedure and Data Analysis

FOIRE-3000 (Shimadzu Co., Japan) performed the fNIRS study. This system uses different laser diodes with wavelength of 780 nm, 805 nm, and 830 nm in order to calculate the cortical activity with a sampling rate of 14 Hz. We obtained 45 channels measurements using 28 optodes (14 light sources and 14 detectors) with the interoptode distance of 30 mm. Fig. 2 showed the channels location and experimental protocol. Based on 10-20 international electrode placement system, the optodes were placed on the parietal lobe which covered the primary sensory-motor cortex, premotor cortex, and prefrontal cortex. Locations of optode were measured using a 3D position measuring system (FASTRAC, Polhemus, USA). The fNIRS data were analyzed using NIRS -statistical parametric mapping (NIRS-SPM). SPM *t*-statistic maps were computed with the level of significance which was set at a p value of < 5% [11].

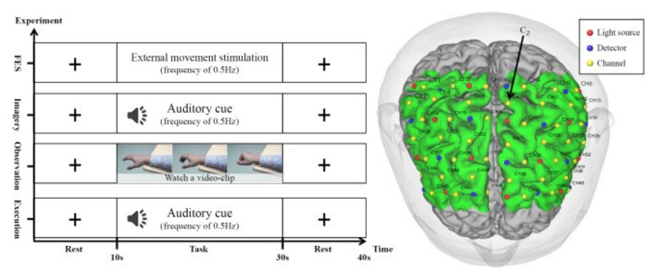


Figure 2. Location of the fNIRS probes and channels in parietal lobe according to 10-20 electrode placement system and experimental protocol.

During fNIRS data analysis, we used the HbO levels as markers of cortical activity because HbO is the most sensitive indicator of changes in regional cerebral blood flow. Moreover, HbO signal changes served as measurements of cortical activation for neurofeedback [6]. After collecting the fNIRS data, signal averaging of the five trials was performed for each condition. In order to investigate the different aspects of changes in HbO during each task, we selected three regions of interest based on the Brodmann area (BA): the primary sensory-motor cortex (BA 1, 2, 3, and 4), the premotor cortex (BA 6), and the prefrontal cortex (BA 8, 9, 44, 45, and 46) [12]. The regions of interest were overlaid on the brain activation image from NIRS-SPM.

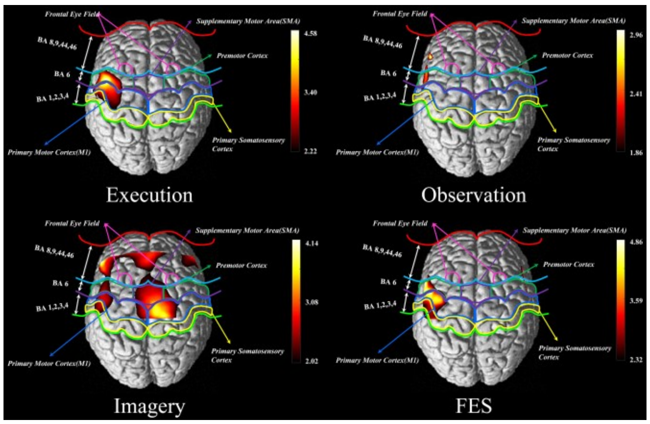
To extract the motor intention, we analyzed the real-time neural signals through a Matlab embedded Labview interface where the online classification algorithm was implemented [13]. The classified motor commands were sent to FES via

TCP/IP protocol in order to provide self-initiated flexion and extension movement of the right hand.

III. Result

A. Execution, FES, Imagery, and Observation

Fig.3 shows the results of group analysis of HbO which indicated activation of the primary sensory-motor cortex (SM1), premotor cortex (PMC), and prefrontal cortex (PFC) during the four conditions of flexion and extension movements of the right hand. Execution activated the contralateral SM1 hand area and the contralateral PMC. The results showed that the active motor execution activated an expected sensorimotor network of brain areas and this activation was stronger than in all other conditions except for the passive movement by FES.



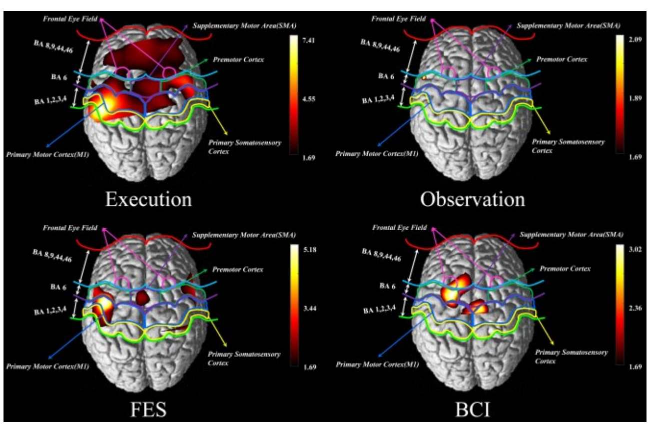


Figure 3. fNIRS results of group analysis. Healthy volunteers (N=7) performed the four 4 modes with the right hand. Activated cortical regions where a significant increase in the HbO leves was detected during the motor execution, action observation, motor imagery, and passive movement by FES. The level of significance was set at a p value = 5%.

Figure 4. fNIRS results of online BCI test. One subject performed the online BCI test who was recruited from the participants in the experiment of this study (Fig. 3). Activated cortical regions where a significant increase in the HbO leves was detected during the motor execution, action observation, passive movement by FES, and Observation-FES integrated BCI. The level of significance was set at a p value = 5%.

FES showed basically the same pattern of activation as that of the execution. It supported that passive movements could activate the same motor function as active motor execution. We discovered that the passive movement activated the same areas as the motor execution, but slightly weaker and narrower in the contralateral SM1. In addition, the passive movement by FES activated sensorimotor areas stronger than imagery and observation.

TABLE I. Accuracy of Online Classification during Observation

	Trials				
	Test 1	***Test 2***	***Test 3***	***Test 4***	***Average***
Accuracy[a] (%)	61.24	67.43	74.92	74.14	69.43

a. The classification accuracy was provided as the AUC measures. AUC, called the area under the ROC (Receiver Operating Characteristics) curve, has been traditionally used in medical diagnosis and a single-number measure for evaluating the predictive ability of machine learning algorithms [13]. In this study, the threshold of AUC for motor command generation was set to 0.75.

Imagery revealed activation in the contralateral SM1 hand area, PMC, and the whole PFC. In addition, the medial part of the SM1 (trunk and shoulder area), and the supplementary motor area was largely activated. The activations in the contralateral SM1 were slightly but significantly stronger in the execution. Taken together, Imagery is predominantly associated with premotor and prefrontal areas, but only moderately with the primary motor and somatosensory areas observed in the execution.

Under the observation, the contralateral PFC was slightly activated with extending into the contralateral PMC. Observation condition had the overall t values (bar index: 1.86 ~ 2.96) which were two times less than those of three conditions. It means that the possibility of the cortical activation during observation (comparing with baseline condition) was much lower than during execution, imagery, and FES. Besides, the observation circumscribed the activation of the sensorimotor cortices considerably connected to the motor function, i.e., the very slight activations of SM1 and PMC. Thus, it could be very difficult to extract the features of motor intention during observation.

B. BCI

It is interesting to note that the activation of observation could become, paradoxically, a source of self-controlled BCI paradigm as previously mentioned (Fig. 1). Despite the fact that classification between the task and the rest is very hard to achieve during observation because it activates only few circumscribed cortices, the extracted subject's intention from the neural signals during observation would be a control input of external stimuli by FES or robotic devices. Comparing observation with a BCI integrating observation with FES, it will be expected that the BCI activates the sensorimotor cortices stronger than the observation. This hypothesis can test that the proposed BCI will be an application of the active motor training.

Fig. 4 showed the result of BCI test of one subject who also participated in the all test of this study. BCI revealed the similar patterns as the group analysis for each condition. As expected, Observation-FES integrated BCI showed the stronger activation compared to that of the observation task. Especially, the contralateral PMC and PFC were mainly activated with slightly extending to the SM1 and supplementary motor area. However, BCI activated the hand region of the SM1 less than FES. It came from that the trials of stimuli in BCI were less than those of FES, because of the low accuracy for classifying the task and the rest during observation (Table. 1). We will attempt to improve the classification performance for larger participants to evaluate and verify the BCI based active motor training paradigm.

IV. Discussion

For the hand grasping task, we investigated the neural activation patterns of three major approaches of stimulating the sensorimotor cortices, i.e. motor imagery, passive movement, and movement observation. The results showed that the brain activity during passive movement by FES was very similar that when motor execution and observation least resembles execution. During observation, the brain activity occurred in the premotor cortex and prefrontal cortex. The dorsolateral prefrontal cortex and premotor cortex are both involved in the mirror neuron system [12]. A mirror neuron is a nerve cell that fires when an individual executes an action and observes the same action being executed by another individual.

A number of previous studies have compared brain activities for the imagery, observation, and execution [2, 3, 4, 6, 7]. Unlike previous studies, our study utilized an fNIRS system as a sensor to extract the motor intention during observation and to control the external stimuli by FES. The attempts of our study may contribute toward promoting the development of active motor training that applies an fNIRS system and FES to post-stroke patients.

There are some limitations to be considered. First, the investigated participants are only recruited from healthy young volunteers. There might be profound difference of cortical activation during same task between healthy subjects and elderly or brain injured patients. Consequently, caution is advised when the groups are compared. Second, the group consisting of seven participants is rather small not to confirm the statistical evaluation of the fNIRS imaging results. Third, the accuracy of classification should make higher to activate motor system stronger for providing more active motor facilitation.

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