Analysis of Key Factors on ERD production for BCI Neuro-robotic rehabilitation

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Abstract—According to recent neuro-rehabilitation research, an appropriate reafferent sensory feedback synchronized with a voluntary motor intention would be effective for promoting neural plasticity during stroke rehabilitation. Therefore, a BCI-based neuro-rehabilitation is considered to be a promising approach. To detect the motor intention, an event-related desynchronization (ERD), which can be evoked by intrinsic motor imagery, is usually used. However there exists various factors that affect ERD production, and its neural mechanism is still an open question. As a preliminary stage for developing an effective neuro-rehabilitation system, in this study, we evaluate the mutual effects of extrinsic (visual and somatosensory stimuli) and intrinsic (spontaneous motor imagery) factors on ERD production. Experimental results indicate that these three factors interact with each other in a complex relationship and probably affect a person’s sense of agency.

I. INTRODUCTION

Because of the rapid aging of the society or a dietary change, there has been an increase in the number of stroke patients. To help them recover from paralysis, it is important for them to receive motor rehabilitation therapy with appropriate assessments from medical doctors and/or therapists. According to these professionals, to promote neural plasticity during the neuro-rehabilitation, these patients should not only perform a passive range of motion exercises, but also should experience reafferent sensory feedback synchronized with a voluntary motor intention.

Although severely impaired stroke patients cannot express their voluntary motor intention, recently, brain–computer interface (BCI) technology has enabled the interpretation of motor intention directly from their brain activities (e.g., an electroencephalogram (EEG)). Especially in BCI neuro-rehabilitation research, degradation of specific sensorimotor rhythms, i.e., event-related desynchronization (ERD), had been widely used for decoding a patient’s motor intention[1], [2], [3], [4], [5], [6], [7], [10], [11], [12]. ERD is known as an EEG feature observed in the human sensorimotor cortex area when actual movement or motor imagery has occurred. Therefore, it can be used as an asynchronous BCI without any external stimuli, unlike a cue-based BCI (SSVEP or P300) [5], [6]. In addition, it is known that the topographical region of ERD production corresponds to a homuncular organization in the human primary motor area. For example, motor imagery for the foot can cause ERD around the center of the motor area (i.e., Cz in the international 10-20 system). Furthermore, ERD can be observed in a narrow frequency band that is specific to each body part, e.g., 9-13 Hz for the hand and 18-23 Hz for the foot.

It is also known that spontaneous ERD production is innately difficult and this ability can be improved with neuro-feedback training. Also, some research reported that observing a video that includes human movement (e.g., a moving hand) induces ERD in healthy subjects without any training[8], [9]. Moreover, other research has found that somatosensory stimulus by a functional electric stimulation (FES) can modulate the motor imagery-based ERD production[1], [3], [7], [10], [11]. Consequently, various factors affect ERD production; however, its neural mechanism is still an open question. As a preliminary stage for developing an effective neuro-rehabilitation system, in this study, we would systematically investigate the mutual effects of extrinsic (visual and somatosensory stimuli) and intrinsic (spontaneous motor imagery) factors on ERD production.

II. METHODS

A. Subjects

Six healthy young volunteers (five males and one female with a mean age of 22.0±1.0 years) participated in the following experiments with written informed consent. All were right-handed and had no neurological disorders. The protocols of the study were approved by the ethical committee at the Tokyo University of Agriculture and Technology.

B. Experimental system

All subjects were seated in a comfortable high-back chair with a foot rest (Fig.1). As shown in the figure, a 23-inch LCD monitor was placed on an angled table located over their thighs, and they were asked to adjust the tilt angle to be able to see the video on the monitor (Fig.2). We used five Ag/AgCl electrodes to take electroencephalogram measurements (g.ACTIVEElectrode, g.tec medical engineering, Austria), and these were placed in the Laplacian derivation layout pattern to cover the sensorimotor area that is considered to be involved in foot motor control, which correspond to Cz in the international 10-20 system. Reference and ground electrodes were located at the left ear lobe and Fz, respectively. The EEG signals were amplified using a multi-telemeter system (WEB5500, NIHON KOHDEN Co., Japan) and recorded...
using a 16-bit A/D-D/A converter (AIO-160802, CONTEC, Japan) with a sampling rate of 256 Hz. A band-pass filter that allowed detection of signals between 0.1 and 100 Hz was applied during measurement. An electrical stimulator (SEN08203, NIHON KOHDEN Co., Japan) and an isolator (SS-104J, NIHON KOHDEN Co., Japan) were used for functional electrical stimulation (FES).

C. Procedure

To clearly understand the differences or the mutual relationships among extrinsic (i.e., visual and somatosensory stimuli) and intrinsic (i.e., spontaneous motor imagery) factors and their effects on ERD production, we obtained an EEG of each subject under seven possible combinations of conditions, as shown in Table I. Four of them were with a visual stimulus, in which subjects saw a video that included a dorsiflexion movement of someone’s left foot from the subjects view point (see Fig.2). Under the FES conditions, subjects received a certain amount of electrical stimulus to the tibialis anterior muscle of their left leg. Furthermore, in the motor imagery condition, subjects were asked to imagine the movement of the left foot.

In the experiment, EEG signals were recorded according to the experimental design shown in Fig.3. As shown in the figure, each trial consists of rest and task periods. The rest period was randomly assigned to last for 5.0-10.0 s, while the task period lasted for 5.0 s. During the rest period, subjects were asked to take a rest while gazing at a fixation point. In contrast, subjects were placed in one of the conditions during the task period. For the following analysis, we dubbed the moment that the task period began as the cue timing, and EEG signals measured before and after cue timing were used for analysis. The trial was repeated 30 times during each condition.

D. Signal Processing

In order to detect the ERD characteristics, the measured signals of the EEG were processed as follows.

First, the raw EEG data were parted by several band-pass filters with a narrow bandwidth (4 Hz) every 1000 ms time window to ascertain the frequency property around the mu and beta bands (5-33 Hz). The filtered signals were squared (i.e., rectified) and time-averaged within each time window. This process was repeated every 125 ms in order to maintain a smooth change of the signal power. After this process, we obtained a time–frequency map (i.e., spectrogram) for each condition.

III. RESULTS AND DISCUSSION

A. Averaged characteristic of ERD

We calculated the average decreasing rate (i.e., the ERD index) to evaluate ERD production during each condition using the following equations [4].

\[
P(f,t) = \frac{\sum_{n=0}^{N} P(f,t+nT)}{N},
\]

\[
ERD(f) = \frac{1}{M} \sum_{i=1}^{M} \frac{P_{\text{task}}^{(i)}(f) - P_{\text{rest}}^{(i)}(f)}{P_{\text{rest}}^{(i)}(f)} \times 100,
\]

where, \(P(f,t)\) is the power of the EEG signal in a certain frequency \(f\) and at time \(t\), \(T\) and \(N\) correspond to a sampling period and a sample size, respectively, for temporal averaging. In this study, we compared the average signal power
between the rest period (2.0 s before the cue timing, $P_{\text{Rest}}(f)$) and task period (2.0 s after the cue timing, $P_{\text{Task}}(f)$). Here $M$ represents number of trials ($M = 30$). For each subject, the frequency $f$ that most decreased in condition VF was used for the determination of the ERD index.

Fig.4 shows the averaged ERD index in each condition. In the figure, a negative index value indicates a large degradation of the signals.

From the averaged results, we can confirm that under condition F (FES only) there were no effects on ERD production. Under condition I (motor imagery only), the results demonstrated that subject B and E showed significant ERD. Moreover, we confirmed that the ERD production during condition FI gets reinforced by the combination of motor imagery and somatosensory stimulus.

Under condition V, all subjects showed ERD in different frequency bands. However, ERD during condition VI is decreased compared with ERD during condition V.

**B. Time-frequency characteristic of ERD**

Fig.5 and Fig.6 show the time-frequency map of each subject under the condition F, FI, I and V, VI, VFI, VF, respectively. These graphs demonstrate transitions of signal power after the cue timing. For the ease of understanding, these data were normalized by the average value of the rest period (2.0 s) just before the cue timing. Therefore, blue regions represent stronger ERD in these graphs.

Therefore, Fig.5 confirms that under condition F, where subjects received only FES without visual stimulus and voluntary motor intention, there were no effects on ERD production. This implies that the somatosensory stimulus alone cannot affect brain activity in the sensorimotor cortex; therefore, we cannot expect that the condition contributes to the neural plasticity.

In condition I, in which subjects performed motor imagery without any extrinsic factors (i.e., typical BCI condition), subject E showed significant ERD in the beta band. This means that the subject originally had the ability to modulate ERD to control BCI devices. However, we cannot find the ERD in subject B, who showed the ERD in Fig.4. The subject might demonstrate significant ERD only in a specific narrow frequency band. Conversely, we confirmed that spontaneous ERD production is innately difficult without any neurofeedback training.

According to the results for subjects C and E, the ERD production ability seems to be reinforced in condition FI, in which subjects have motor imagery with FES. We can speculate that ERD might be produced when both spontaneous motor intention (i.e., motor imagery) and appropriate sensory feedback synchronized with the intention are simultaneously satisfied, and it might affect a person’s sense of agency.

On the other hand, Fig.6 shows a relatively explicit ERD (blue region). This implies that visual stimulus is highly affective on ERD production, although ERD is considered as an EEG feature for asynchronous BCI without any external stimuli.

Comparing the results from conditions V and VI, or VF and VFI, we can observe that motor imagery does not necessarily improve ERD production instead it seems to be an interference. This suggests that these three factors do not always additively interact with each other. As previously noted, voluntary motor intention together with reafferent sensory feedback causes ERD production, but in this situation, there might be a mismatch in cognition with a sense of agency.
Fig. 5. Time-frequency map (Condition F, FI, and I). Vertical axis shows frequency bands (5-33 Hz), while horizontal axis indicates elapsed time after the cue (0.0-3.0 s).
IV. CONCLUSIONS

In this study, we evaluated the mutual effects of extrinsic (visual and somatosensory stimuli) and intrinsic (spontaneous motor imagery) factors on ERD production.

The experimental results obtained by us are follows: (1) Spontaneous ERD production is innately difficult without any neuro-feedback training. (2) Somatosensory stimulus alone cannot affect the brain activity in the sensorimotor cortex; therefore, it cannot be expected that the condition contributes to the neural plasticity. (3) The ERD might be produced when both spontaneous motor intention (i.e., motor imagery) and appropriate sensory feedback synchronized with the intention are simultaneously satisfied. (4) The visual stimulus is highly affective on ERD production, although ERD is considered as an EEG feature for asynchronous BCI without any external stimuli. (5) The three factors on which this study focused interact with each other in a complicated relationship and probably affect a person’s sense of agency. Also, we confirmed that the frequency band for ERD production is highly dependent on each subject.
Based on these findings, we will develop an EEG-FES based neuro-rehabilitation system for stroke patients.

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