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RESEARCH ARTICLE

Event-related desynchronization possibly discriminates the kinesthetic illusion induced by visual stimulation from movement observation

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Abstract
Visual stimulation of a repetitive self-movement image can evoke kinesthetic illusion when a virtual body part is set over the actual body part (kinesthetic illusion induced by visual stimulation, KINVIS). KINVIS induces activity in cerebral network, similar to that produced during motor execution, and triggers motor imagery passively. This study sought to identify a biomarker of KINVIS using event-related desynchronization (ERD) to improve the application of KINVIS to brain–machine interface (BMI) therapy of patients with stroke with hemiparesis. We included healthy adults in whom KINVIS could be induced. Scalp electroencephalograms were recorded during the KINVIS condition, where KINVIS was induced using a self-movement image. The findings were compared to signals recorded during an observation (OB) condition where only the self-movement image was viewed. For the signal intensity of the α- and low β-frequency bands, we calculated ERD during a movie period. The ERD of the α-frequency band in P3 and CP3 during KINVIS was significantly higher than that during OB. Furthermore, using the ERD of the α-frequency band recorded from FC3 and CP3, we could discriminate illusory perception with a 70% success rate. In this study, KINVIS could be detected using the ERD of the α-frequency band recorded from the posterior portion of the sensorimotor cortex. Furthermore, adding ERD recorded from FC3 to that recorded from CP3 may enable the objective discrimination of KINVIS from OB. When applying KINVIS in BMI therapy, the combination ERD of FC3 and CP3 will become a parameter for objectively judging the degree of kinesthetic perception achieved.

Keywords Kinesthetic illusion · Event-related desynchronization · Electroencephalogram · Brain–machine interface · Embodiment · Body ownership

Introduction

Kinesthetic illusion, the sensation of movement in one's own body, is induced by various sensory inputs, even in the absence of voluntary or passive movement. Kaneko et al. (2007) reported that visual stimulation using a repetitive self-movement image evokes a kinesthetic illusion when a virtual body part is set over its actual counterpart; this phenomenon is referred to as kinesthetic illusion induced by visual stimulation (KINVIS). This system can be viewed as a virtual reality (augmented reality) intervention using embodied-visual feedback, which can induce embodied cognitive change in self-body and physiological effects on motor-associated areas in the brain (Kaneko et al. 2007; Aoyama et al. 2012; Kaneko et al. 2015, 2016a, b). In other words, kinesthetic illusion may represent a cognitive stimulation to the embodied-brain system for body ownership, sense of agency, and kinesthetic perception. We have used electrophysiological methods and functional magnetic resonance imaging (fMRI) to reveal that KINVIS increases activation of cerebral networks, including higher-order motor and sensory processing areas of the superior and inferior parietal lobes, and excitation of the corticospinal tract (Kaneko et al. 2007; Aoyama et al. 2012; Kaneko et al. 2015); such enhancement of cerebral network activity resembles that which corresponds to motor execution and occurs when the self-movement image is viewed. These reports suggest that

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KINVIS can passively induce the sensation of movement. In addition, KINVIS is the psychological representation of movements induced involuntarily, whereas motor imagery is the action reflecting the image of movement voluntarily. According to one stroke patient's reflection during KINVIS, "I recalled the feeling of moving my limbs and so I wanted to move them" (Kaneko et al. 2016a).

Recently, the application of a non-invasive, motor output-type brain–machine interface (BMI) that uses scalp electroencephalography (EEG) has been used in rehabilitation programs for patients with stroke with hemiparesis. With this motor-output type BMI, the scalp EEG records and analyzes electrophysiological cortical activity during motor imagery. When event-related desynchronization (ERD) in the α-frequency band of the sensory-motor cortex was detected, the patients' motor-driven orthosis was triggered to extend their paralyzed fingers. ERD is characterized by EEG amplitude attenuation, which is induced by specific phenomena such as motor execution or sensory simulation (Pfurtscheller and Lopes da Silva 1999). During motor execution and imagery, the frequency component of the 8–13 Hz band of the sensorimotor cortex decreases (Sensorimotor rhythm or Mu rhythm) (Neuper and Pfurtscheller 2001; Neuper et al. 2005; Ushiba and Soekadar 2016). Shindo et al. (2011) investigated the effect of BMI training on motor function in patients with stroke with moderate to severe hemiparesis. As in the BMI training, patients imagined their fingers extending, during which EEG recorded activity in the sensorimotor cortex. When ERD was induced, the motor-driven orthosis was triggered to passively extend the finger. This training was performed for 1–2 h per week for a period of 4–7 months. As a result, the EMG of the common digital extensor muscle increased during finger extension. Furthermore, the success rate of ERD during motor imagery increased in half of the subjects with a concomitant increase in ERD intensity. This finding demonstrated that BMI training is effective for recovering motor function in patients with stroke with hemiparesis (Shindo et al. 2011). Further clinical application of this intervention is expected.

In contrast, motor imagery is difficult to perform in patients with severe stroke symptoms, including hemiparesis, as well as among the elderly (Dettmers et al. 2012). As aforementioned, KINVIS induces cerebral network activity resembling that which is prompted by motor execution and is able to induce motor imagery passively. KINVIS may, therefore, render BMI training feasible, even for patients who cannot voluntarily recall motor imagery. However, many studies have used subjective questionnaire-based evaluations to determine if KINVIS is induced in subjects. Thus, it is difficult to objectively and easily evaluate psychological states during KINVIS.

Research using transcranial magnetic stimulation (TMS) to study the association between the ERD intensity of the Mu rhythm and corticospinal tract excitability found that the ERD of the Mu rhythm reflects the excitability of the primary motor cortex (Takemi et al. 2013). As corticospinal tract excitability increases during KINVIS, we speculated that the specific cerebral network activity accompanying KINVIS is also likely to be detected by ERD. Moreover, Mu rhythm ERD is a parameter in BMI training using motor imagery. It is necessary to clarify a biomarker of KINVIS for application of KINVIS in BMI training. The purpose of this study was as follows: (1) to use EEG to identify a biomarker of kinesthetic perception and (2) to verify whether KINVIS can be discriminated using ERD as a parameter.

Materials and methods

Subjects

The present study included 10 healthy right-handed adults (age, 20.1 ± 1.6 years; height, 170.1 ± 5.2 cm; and weight, 58.2 ± 5.2 kg). Each participant provided informed consent for participation in this study, consistent with the Declaration of Helsinki. This study was approved by the Ethics Committee of Sapporo Medical University.

Procedure

The subjects were seated in a chair with their forearms placed on the experiment table, which was raised to a comfortable height to maintain the resting position. Training to intensify KINVIS was performed in advance. After confirming that KINVIS was induced (see below, section KINVIS), EEG signals were recorded under two conditions. In the first condition, the position of the monitor was adjusted to cover the subject's forearms. Then, by providing visual stimulation via a repetitive self-movement image, KINVIS was induced (KINVIS: Fig. 1a). In the second condition, the monitor was set in front of the subject and the same video that was used in the KINVIS condition was displayed (OB: Fig. 1b). In OB condition, their real hand was beside the monitor on which the pre-recorded movie of the self-movement hand was projected. Therefore, the subjects were watching the resting real hand and picture of self-movement simultaneously, consequently the subjects recognized their real hand actually did not move. As a control condition, we established "observation". This is because one of the purposes of the study was to define the biomarker discriminating whether KINVIS could be induced in the same environment that allowed observing a self-movement image.

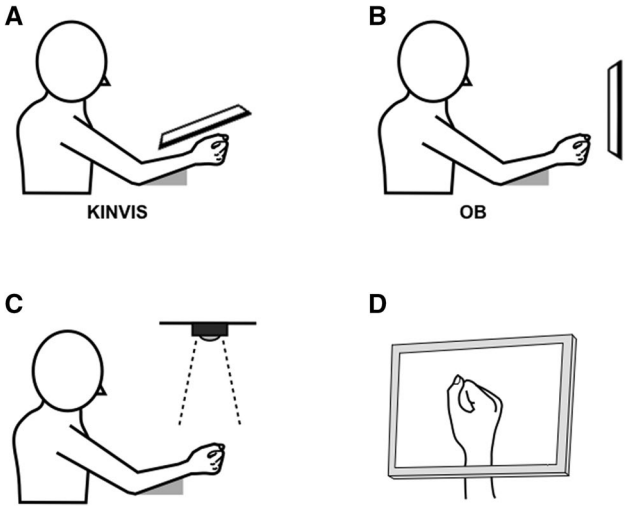

Fig. 1 Experimental conditions and method of KINVIS induction. In the KINVIS condition, the monitor was placed such that the forearm in the video overlapped with the subject's actual forearm from the subject's viewpoint (**a**). In the OB condition, the monitor was placed perpendicularly across the subject and the video used in the KINVIS condition was displayed. The monitor was adjusted such that both the subject's hand and the hand in the video were visible to the subject (**b**). To make the video, the camera was placed directly above the subject's hand to record a video of his or her hand movement (**c**). The recorded video was displayed such that the forearm in the video mirrored the subject's actual forearm from the subject's viewpoint (**d**)

KINVIS

KINVIS was performed using a method previously reported by Kaneko et al. (2007). A pre-recorded video showing a hand grasp/open movement performed every 6 s was used as a visual stimulus. We used a web camera (Webcam C920t, Logicool HD Pro, Switzerland) to make the video. The camera was positioned directly above the subject's right hand from the perspective of the subject; the camera lens was parallel to the table (Fig. 1c). The recorded video was then displayed on a monitor set on the subject's forearm to cover his or her right hand; this arrangement allowed for the forearm in the video to be continuous with the actual forearm (Fig. 1d). All subjects received training, which entailed watching the video until KINVIS was adequately induced (KINVIS training). The KINVIS training included four sets, each lasting 5 min. After the KINVIS training, the subject's agreement to the response "I felt as if my own hand was moving" was rated on a 7-point Likert scale (from − 3: I completely disagree, to + 3: I very much agree).

EEG

After the KINVIS training, we measured EEG during both conditions. The video was displayed for 12 s (2 cycles) in both conditions (Fig. 2). The starting time of the video was

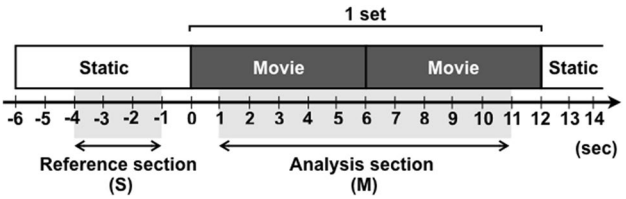

Fig. 2 Analysis interval. The reference section was 3 s during the display of the static image. The 10 s from the start of the video display, at 1 s, was the analysis section

randomized and an interval of ≥ 30 s was set between the trials; before and after the video start time, the image of the static hand was displayed. Each trial was performed 20 times.

A 64-multichannel EEG system (eego™ sports, ANT Neuro) was used to measure EEG. The mean of all electrodes recorded using the average potential reference was used as the standard. The recording was made with an electrode impedance and sampling frequency of ≤ 20 Ω and 500 Hz, respectively. During each trial, all subjects were instructed not to move or blink. Moreover, trials featuring blinking or electromyogram (EMG) signals ≥ 50 μV briefly induced in the extensor carpi radialis (ECR) and flexor carpi radialis (FCR) were excluded. Neuropack (MEB2200, Nihon Kohden, Tokyo) was used to record EMG signals. Surface plate electrodes were placed on each muscle with an inter-electrode distance of 18 mm. To minimize electrical resistance of the skin, the skin was cleaned with disinfectant alcohol and abraded with an abrasive skin-prepping gel in advance of testing. The EMG was recorded at a sampling frequency of 20 kHz using an A/D converter and then transmitted to a personal computer.

Data analysis

We analyzed the following electrodes positioned according to the international 10–10 system: F3, F4, FC3, FC4, C3, C4, CP3, CP4, P3, and P4 (Fig. 3). ERD analysis was performed using a previously reported method that investigated the effect of BMI training on motor function in patients with stroke (Shindo et al. 2011). The EEG signals measured by each electrode were filtered using a band-pass filter (1–50 Hz). The Fast Fourier Transform (FFT) was used to analyze time frequency. Frequency resolution was set to 1 Hz, and 1-s FFT was performed every 100 ms. Next, with the mean EEG amplitude in the static image period (*S*) set as the standard, we calculated the ratio of the decrease in EEG amplitude over a 10-s period (*M*), 1 s after the video was started (Fig. 2, formula 1). ERD of each trial was calculated with a resolution of 1 Hz, and the mean of 20 trials were calculated:

$$\mathrm{ERD} = \frac{S-M}{S} \times 100 \quad (1)$$

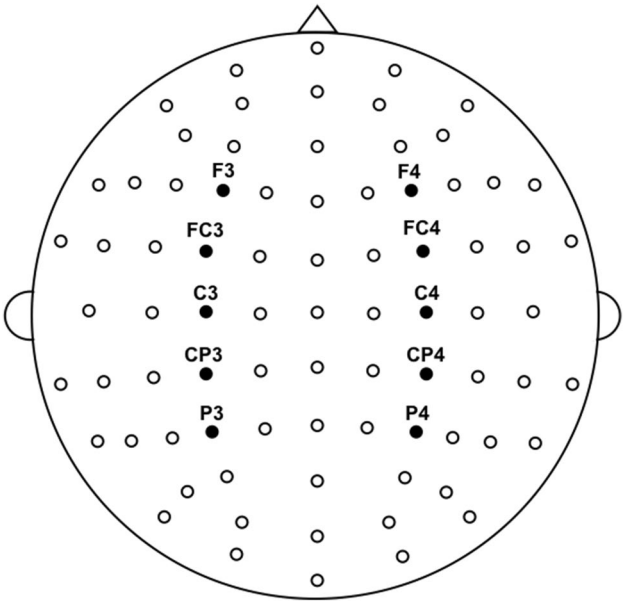

Fig. 3 Clear circles indicate the positions of the international 10–10 system. In this study, mean signal values obtained from all the electrodes were references. The analysis sites included the following 10 electrodes shown as black circles: F3, FC3, C3, CP3, P3, F4, FC4, C4, CP4, and P4

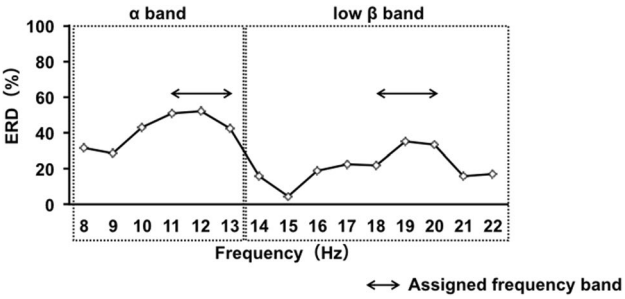

Fig. 4 Method of calculating the analysis frequency bands. In the α- (8–13 Hz) and low β- (14–22 Hz) frequency bands. The analysis the frequency bands used to calculate the mean ERD were those that featured the highest ERD values, as well as those 1 Hz before and after (totaling to 3 Hz)

In the α- (8–13 Hz) or low β- (14–22 Hz) frequency bands, the analysis frequency bands were those that featured the highest mean ERD values, as well as those found 1 Hz before and after (highest ERD ± 1 Hz) (Fig. 4). And, ERD in the analysis frequency bands (totaling to 3 Hz) were averaged per frequency band.

Statistical analysis

IBM SPSS Version 23.0 (IBM, USA) was used for all statistical analyses. Regarding the sensation of illusion, Wilcoxon signed-rank sum tests were performed for all trial

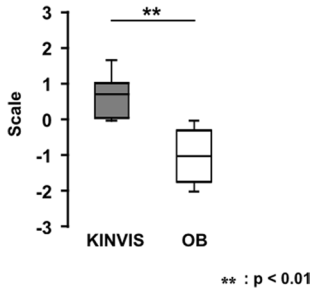

Fig. 5 Median value of the 7-point Likert scale in each condition shown to 4 decimal places. The error bar indicates the maximum and minimum values. $^{**}p < 0.01$

condition factors. For ERD, a repeated measure two-way factorial analysis of variance (ANOVA) was performed with the analysis sites (F3, F4, FC3, FC4, C3, C4, CP3, CP4, P3, and P4) and trial conditions (KINVIS, OB) as factors at each frequency band. If a significant interaction was present, a simple main effect test based on the Bonferroni method was performed as post hoc test. Based on these results, we performed a discrimination analysis using the sensation of illusion as the dependent variable. The status of the sensation of illusion was considered the objective variable, and the ERD of the various analysis sites in the α-frequency band, where significant main effects were observed in the KINVIS and OB conditions, as the explanatory variable. The KINVIS condition was considered as "sensation of illusion present" and the OB condition as "sensation of illusion absent." We used a stepwise method for the discrimination analysis to select the explanatory variable. The level of significance was set to 5%.

Results

The median value (within 4 decimal places) for perceived illusion in OB was − 1.00 (− 2.00 to 0.00), and in KINVIS was 1.00 (0.00–1.00), showing a significantly higher value in KINVIS [$Z = -2.810$, $p = 0.005$, Fig. 5].

The results of the time–frequency analysis in a typical case are presented in Fig. 6 (KINVIS: A, OB: B), while the mean values for all subjects are presented in Fig. 7 (α-frequency band: A, β-frequency band: B). The results of a two-way factorial ANOVA revealed that there was a significant interaction between the trial conditions and analysis site factors [$F(2.205,19.842) = 4.325$, $p = 0.025$] for the α-frequency band. Moreover, the post hoc test indicated the ERD for CP3 and P3 during KINVIS were significantly higher than that during OB. In contrast, there was no significant interaction of 2 factors in the low β-frequency band [$F(3.389,30.504) = 1.134$, $p = 0.355$]. Moreover, in both the α-frequency and β-frequency bands,

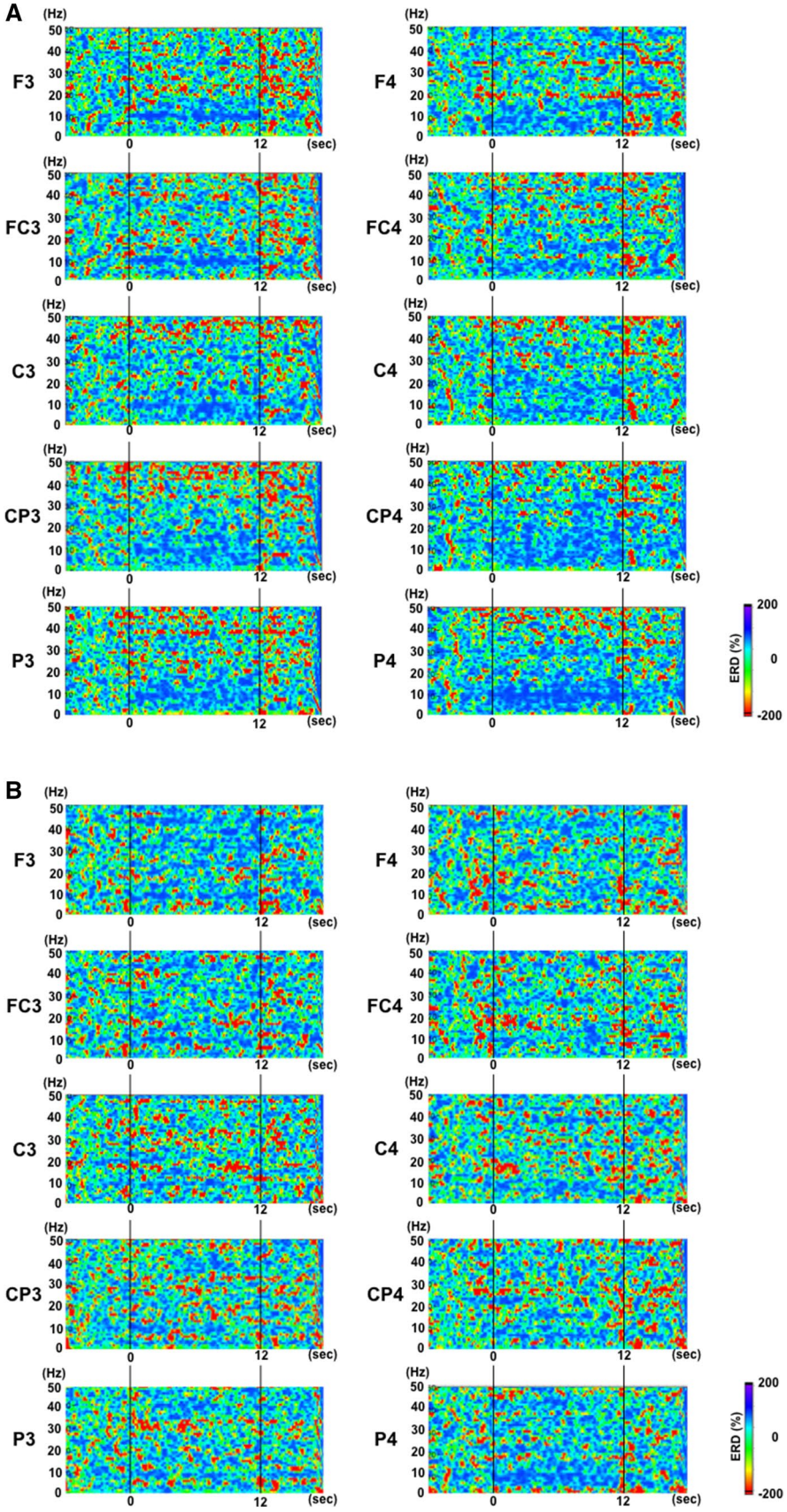

Fig. 6 Results of the time–frequency analysis in each condition (KINVIS condition: **a**, OB condition: **b**). The video was displayed in the 0–12-time band. On the spectrum from red to blue, values closer to blue indicate a higher ERD

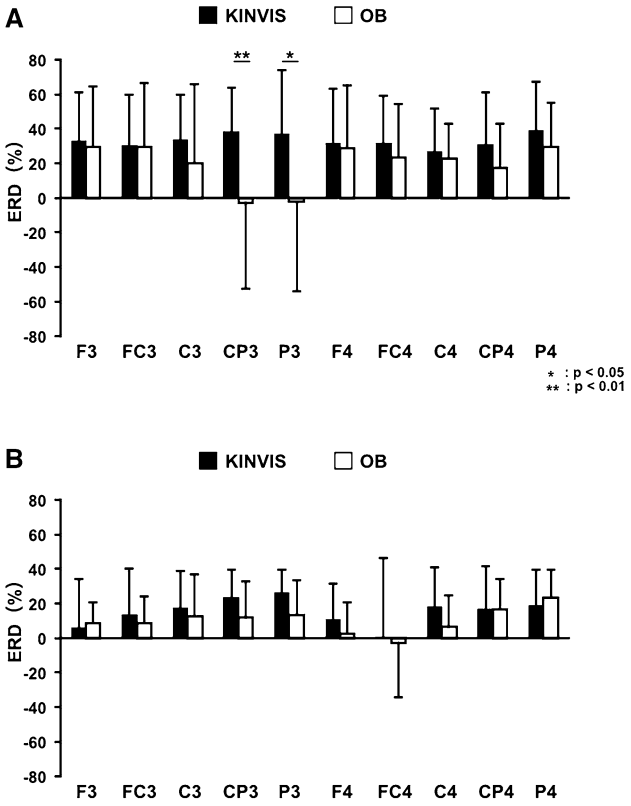

Fig. 7 Mean ERD during the video display in each condition (α-frequency band: A, low β-frequency band: B) The error bar indicates the standard deviation. $*p<0.05$, $**p<0.01$

there were no significant main effects of the trial condition factors [α-frequency band: $F(1,9)=2.920$, $p=0.122$, low β-frequency band: $i(1,9)=0.802$, $p=0.394$] or analysis site factors [α-frequency band: $F(2.437,21.933)=2.144$, $p=0.133$, low β-frequency band: $F(1.601,14.409)=2.678$, $p=0.111$].

Based on these results, the KINVIS condition was judged as "sensation of illusion present" and the OB condition as "sensation of illusion absent." A discrimination analysis was performed for the correlation between the status of the sensation of illusion and ERD. The status of the sensation of illusion was considered the objective variable, and the ERD of the various analysis sites in the α-frequency band, where significant main effects were observed in the KINVIS and OB conditions, as the explanatory variable. We used a step-wise method for the discrimination analysis and the level of significance was set at 5%. The selected variables were the ERD in FC3 and CP3, and the included functions of both FC3 and CP3 were significant. Regarding the discriminant function, when $p=0.018$ and the discriminative rate was 70.00%, the correlation ratio was 0.615 (Table 1). The median of the discriminant coefficient was 0.740 for the "sensation of illusion present" group and − 0.740 for the "sensation of illusion absent" group.

Table 1 The discrimination coefficient

Number of variables	Correlation ratio
2	0.615*
Number of variables	Discrimination coefficient
FC3	− 1.096 *
CP3	1.492 *

$n=20$, predictive value: 70.0%

$*p<0.05$

Discussion

The present study investigated ERD during KINVIS and motor observation using scalp EEG. Our results revealed that the ERD of the α-frequency band during KINVIS significantly increased relative to that recorded during motor observation. The difference between the approaches was evident, particularly concerning data collected from CP3 and P3. Moreover, each participant felt as if his or her own hand was moving under the KINVIS condition, while none felt a similar sensation under the OB condition. This result may indicate that the difference in ERD between the two conditions reflects the cerebral activity associated with the sensation of illusion.

Of the EEG frequencies recorded from the sensorimotor cortex at rest, those in the 8–13 Hz band are referred to as Mu rhythm (or sensorimotor rhythm). It was reported that Mu rhythm appears at rest and disappears when there are active movements and somatosensory stimulation (Chagrin 1976). Furthermore, Mu rhythm decreases during motor imagery and the observation of the actions of another human (Altschuler et al. 1997; Cochin et al. 1998, 1999; Gastaut and Bert 1954; Muthukumaraswamy et al. 2004; Neuper and Pfurtscheller 2001; Neuper et al. 2005; Ushiba and Soekadar 2016). In the present study, Mu rhythm ERD magnitudes in C3 increased during observation. In addition, subjects observed the actions of the right arm, and the Mu rhythm ERD was recorded from the ipsilateral cortex C4. In the previous study that measured EEG during the observation of a grasping movement, ERD occurred on both sides of the sensorimotor cortex (Muthukumaraswamy et al. 2004). The present study did not contradict this.

During KINVIS, Mu rhythm ERD in both hemispheres of the sensorimotor cortex occurred in the present study. A previous report on Mu rhythm ERD during motor imagery revealed that Mu rhythm ERD reflected cerebral cortex excitability (Takemi et al. 2013). Moreover, corticospinal tract excitability increased and intracortical inhibition decreased when Mu rhythm increased, suggesting that Mu rhythm ERD reflects primary motor cortex excitability. During KINVIS of index finger abduction, Kaneko et al.

(2007) performed TMS on the primary motor cortex and recorded motor-evoked potentials (MEP) from the first dorsal interosseous. They reported that MEP amplitude during index finger abduction increased when KINVIS occurred, compared to motor observation under which KINVIS was absent. This result demonstrated that even when the same repetitive self-movement image was presented, the excitability of the primary motor cortex only increased during KINVIS, not changed during simple motor observation. Considering these previous reports, it is suggested that the excitatory increase of the primary motor cortex during KINVIS might influence Mu rhythm ERD. However, the present study found that there was no difference between the KINVIS and OB conditions in Mu rhythm ERD, namely ERD of the α-frequency band recorded from C3 that reflects primary motor cortex excitability. We thus cannot confirm whether the ERD in C3 was induced by kinesthetic perception elicited by a self-movement image or whether it was induced by visual stimulation.

In the present study, the α-frequency band amplitude in the posterior portion of the sensorimotor cortex decreased in both conditions. The α-frequency rhythm in the posterior portion of the sensorimotor cortex is functionally different from that of the sensorimotor cortex. The α-frequency rhythm in both sensorimotor and posterior portion of the sensorimotor cortex appears at rest and disappears during sensory stimulation (Rizzolatti et al. 2001). In particular, the α-frequency rhythm in the posterior portion of the sensorimotor cortex appears when the visual system does not function. The results of this study showed that the amplitude of the α-frequency rhythm in the posterior portion of the sensorimotor cortex decreased in both conditions, during KINVIS and observation. This is in line with a previous study that reported that the α-frequency rhythm in the posterior portion of the sensorimotor cortex disappeared when the visual system was functional. However, the ERD in P3 and CP3 revealed a difference between the KINVIS and OB conditions. We speculate that the factor that affected the ERD of P3 and CP3 is something other than the visual system, as the visual system functions during both conditions. A previous study exploring cerebral networks using fMRI found that parietal lobe activity increased during KINVIS relative to a control condition, which featured a video of the hand of another person that did not induce KINVIS (Kaneko et al. 2015). Thus, in this study, we speculate that the specific activity that occurs in the parietal lobe during KINVIS affects the ERD in P3 and CP3.

In this study, when the ERD of the FC3 and CP3 α-frequency bands were used as a parameter, the status of the KINVIS or OB conditions could be discriminated at a probability of 70%. The difference between two conditions was whether KINVIS occurs in the subjects. According to the international 10–20 system, FC3 corresponds to the left premotor cortex and CP3 corresponds to a site located midway between P3, which corresponds to the left superior parietal lobe (Okamoto et al. 2004), and the sensorimotor cortex. Previous studies have found that the premotor cortex was activated during kinesthetic perception induced by sensory input with tendon vibration (Naito et al. 1999; Romaiguere et al. 2003; Kavounoudias et al. 2008). Furthermore, the premotor cortex activity increased during kinesthetic perception induced by a visual stimulation using a self-movement video (Kaneko et al. 2015). Distinct functional and anatomical pathways link different regions of the inferior parietal lobule with the ipsilateral motor cortex (Koch et al. 2010). In addition, a neuroimaging study has demonstrated that the superior longitudinal fasciculus connects a wide range of frontal and parietal areas (Thiebaut de Schotten et al. 2011). The activity of the frontal-parietal network increases when subjects perceive the kinesthetic illusion of the right wrist movement induced by tendon vibration (Naito et al. 2016). The frontal-parietal network is involved in the sensation of body ownership and kinesthetic illusion (Naito et al. 2005; Amemiya and Naito 2016). Therefore, we speculate that the activity of the frontal and parietal areas might change during KINVIS, and this activity in the frontal-parietal network associated with KINVIS affects the FC3 and CP3 network in the α-frequency band.

The present study used EEG for the following purposes: (1) to clarify the biomarker of kinesthetic perception using EEG and (2) to verify whether KINVIS can be discriminated using ERD as a parameter. Our findings revealed that KINVIS induced characteristic activity that could be detected as the ERD of the α-frequency band recorded at P3 and CP3, namely the posterior portion of the sensorimotor cortex. However, the status of KINVIS could not be discriminated from the ERD of P3 or CP3 alone. In contrast, combining the ERD collected from FC3 and CP3, namely the anterior and posterior portion of the sensorimotor cortex, would enable objective discrimination of the status of KINVIS or OB conditions with high probability. When applying KINVIS in BMI therapy, the combination ERD of the FC3 and CP3 will become a parameter for objectively judging the degree of kinesthetic perception achieved. Nonetheless, these results must be interpreted with caution, because this study has the relatively small sample size. Therefore, a further large-scale detailed study is warranted to explore the possibility of using ERD as a parameter for applying KINVIS BMI therapy for improving sensory-motor functional impairments in patients with stroke. Furthermore, using ERD online analysis, it may be possible to confirm whether ERD changes when KINVIS occurs and whether ERD of patients with stroke patient changes during KINVIS.

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