Event-Related EEG Desynchronization Reveals Enhanced Motor Imagery From the Third Person Perspective by Manipulating Sense of Body Ownership With Virtual Reality for Stroke Patients

Xiaotian Xu, Xiaoya Fan, Jiaoyang Dong, Xiting Zhang, Zhe Song, Wei Li, and Fang Pu

***Abstract*— Virtual reality (VR)-based rehabilitation training holds great potential for post-stroke motor recovery. Existing VR-based motor imagery (MI) paradigms mostly focus on the first-person perspective, and the benefit of the third-person perspective (3PP) remains to be further exploited. The 3PP is advantageous for movements involving the back or those with a large range because of its field coverage. Some movements are easier to imagine from the 3PP. However, the 3PP training efficiency may be unsatisfactory, which may be attributed to the difficulty encountered when generating a strong sense of ownership (SOO). In this work, we attempt to enhance a visual-guided 3PP MI in stroke patients by eliciting the SOO over a virtual avatar with VR. We propose to achieve this by inducing the so-called out-of-body experience (OBE), which is a full-body illusion (FBI) that people misperceive a 3PP virtual body as his/her own (i.e., generating the SOO to the virtual body). Electroencephalography signals of 13 stroke patients are recorded while MI of the affected upper limb is being performed. The proposed paradigm is evaluated by comparing event-related desynchronization (ERD) with a control paradigm without FBI induction. The results show that the proposed paradigm leads to a significantly larger ERD during MI, indicating a bilateral activation pattern consistent with that in previous studies. In conclusion, 3PP MI can be enhanced in stroke patients by eliciting the SOO through induction of the "OBE" FBI. This study offers more possibilities for virtual rehabilitation in stroke patients and can further facilitate VR application in rehabilitation.**

***Index Terms*— Electroencephalograph (EEG), event-related desynchronization (ERD), full-body illusion (FBI), motor imagery enhancement, virtual reality (VR).**

NOMENCLATURE

AO:	Action observation.
CT:	Computerized tomography.
C-MI:	Control MI.
EEG:	Electroencephalographic.
ERD:	Event-related desynchronization.
ERSP:	Event-related spectral perturbation map.
E-MI:	Enhanced MI.
FBI:	Full-body illusion.
HMD:	Head-mounted display.
MI:	Motor imagery.
MRI:	Magnetic resonance imaging.
M1:	Primary motor areas.
OBE:	Out-of-body experience.
RHI:	Rubber hand illusion.
SOO:	Sense of body ownership.
STFT:	Short-time Fourier transform.
VR:	Virtual reality.
1PP:	First-person perspective.
3D:	Three-dimensional.
3PP:	Third-person perspective.

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Local Ethics Committee of Binzhou Medical College under Application No. KT-59, and performed in line with the Declaration of Helsinki.

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I. INTRODUCTION

VIRTUAL reality (VR)-assisted motor training is a promising rehabilitation method for stroke patients [1], [2], [3], [4] that can be integrated with mirror therapy [5], motor imagery (MI) [6], [7], [8], [9], [10], action observation (AO) [11], rehabilitation robotics [12], and other conventional training methods for promoting motor recovery. Among these methods, MI is widely used for motor function recovery in stroke patients [13]. It leads to activation of the motor and motor-related regions without physically performing the motor task, making it optimal for patients with limited motor functions [14], [15]. Meta-analysis has revealed the significant effects of MI training for stroke patients on various aspects of motor functionality [16], such as gait [17], balance [17], and active range of motion [18], among others.

However, the training efficiency of pure MI is far from ideal, and different approaches have been proposed to enhance MI. A typical method is the usage of action observation, that is, providing visual guidance by presenting target motions [19]. Compared to independent MI, the increased activation of the motor system during MI with AO has been consistently reported [20], [21]. Teresa et al. compared the brain activation between MI guided by two- and three-dimensional (3D) videos [22]. Their results revealed a pronounced event-related desynchronization (ERD) of the α band over the sensorimotor cortices when guided by 3D videos, which indicated improved MI. The enhanced MI was attributed to a richer and realistic visual guidance. The VR technology has been used to provide richer visual guidance. VR usage further improves MI [6] because it recruits the sensory modality of vision better while reducing distractions from the surroundings by providing an immersive virtual environment [23]. A different, but very interesting, approach attempts to maximize the rehabilitation effects of MI by incorporating the rubber hand illusion (RHI) [24]. The rationale underlying this paradigm is that people might have a feeling of moving their own hand because the RHI can induce a strong ownership to the fake rubber hand, thereby directly inducing MI. The virtual hand illusion has also been used to enhance MI [25]. However, the two abovementioned methods have only been validated with visual cues in the first-person perspective (1PP).

Apart from the 1PP [11], [26], visual guidance can also be provided with a third-person perspective (3PP) [27]. Visual cues from the 3PP have advantages compared with those from the 1PP. First, 3PP viewpoints could overcome the field of view limitations of the 1PP [28], [29]. Second, some axial movements like shoulder shrugging are more easily imagined from the 3PP [30]. However, training may be less effective when the visual cue is from the 3PP [31]. Tambone et al. compared VR-based gait training while the participants watching the virtual avatar walking forward from either 1PP or 3PP. Their data showed that only 1PP visual guidance resulted in improved gait and balance. The difference in the training outcome was attributed to the presence/absence of an illusory sense of body ownership (SOO) to the virtual avatar [31].

The SOO is a subjective experience during which one perceives an object as his/her own body or body part [32]. A shared electrophysiology mechanism of body ownership and motor imagery has been previously reported, showing that the SOO can activate the motor system without motor execution [33]. The illusory SOO over a virtual avatar from the 3PP can be experienced by inducing the full-body illusion (FBI) that people observe/perceive the virtual avatar as their own, similar to the so-called out-of-body experience (OBE) [34]. The "OBE" FBI has been successfully induced in healthy individuals by Ehrsson et al. and Lenggenhager et al. through a synchronous visuo-tactile stimulus to a virtual avatar placed 2 m in front of their physical bodies [34], [35]. In stroke patients, the neural pathways involved in the SOO formation may remain intact or partially preserved [31] because the SOO can successfully be elicited by a synchronous visuo-tactile stimulus [36], [37], [38].

Taken together, we speculate that by inducing the SOO over a virtual avatar from the 3PP through the "OBE" FBI in stroke patients, the efficiency of the VR-guided rehabilitation training from the 3PP can be improved, thereby providing more possibilities for virtual rehabilitation. We chose MI as the rehabilitation method to test our hypothesis because it has been widely used for post-stroke rehabilitation [26]. In this study, 13 patients with stroke were recruited. We tested our hypothesis by comparing the brain activations of two paradigms, that is, with and without the "OBE" FBI, by calculating the ERD from electroencephalographic (EEG) signals, which is a widely acknowledged and well-established method.

II. METHODS

A. Participants

The inclusion criteria were as follows: (1) under the age of 80; (2) diagnosed with stroke through computerized tomography (CT) or magnetic resonance imaging (MRI); (3) first stroke and with unilateral dyskinesia; (4) absence of severe cognitive impairment or a history of psychiatric illness; and (5) capable of understanding experimental requirements and completing the entire experiment. Thirteen individuals who suffered from stroke (6 women, 7 men, mean age 60.9 ± 11.3, between 40 and 73) were recruited from the Department of Rehabilitation, Affiliated Hospital of Binzhou Medical College. Seven of which had left hemisphere damage, while six had right hemisphere damage. They had an average Fugl-Meyer assessment score of 87.54 ± 4.17. Six patients had mild dyskinesia, and one had significant dyskinesia. The eligibility of all patients was determined by experienced medical personnel. All participants provided written informed consent before taking part in the study. The study was approved by the local ethics committee of Binzhou Medical College (KT-59).

B. Experimental Design and VR Device

The participants were immersed in a virtual environment showing a life-sized avatar sitting on a stool with a 420 mm height at the center of a virtual room that was 5 m long, 5 m wide, and 3 m high. The avatar was situated approximately 2 m straight ahead of the participants' viewpoint, with its back straight, arms hanging naturally at its sides, and legs joined. The participants had a full view of the virtual avatar from its back. Their viewpoint was aligned to the height of the avatar's eyes. The VR scene was developed using the Unity 3D engine of Unity Technologies of San Francisco (CA, USA) and the SteamVR SDK.

The experiment was conducted in a room measuring approximately 20 m^2, where two VIVE infrared locators were diagonally placed at two opposing corners to create a VR environment of roughly 15 m^2. A valve index head-mounted display (HMD) was used to present the VR scene, providing a monocular resolution of 1440*1600 px, a 130° horizontal visual range, and a 144 Hz refresh rate. This immersive device enabled virtual environment rendering in a 360° stereoscopic view, which was crucial for inducing the "OBE" full-body illusion. We induced the illusion following the approach proposed by Lenggenhager et al. [34] with a synchronous visuo-tactile stimulation. The tactile stimulus was given on the participants' back using a physical stick, whose trajectory was tracked by an HTC VIVE Tracker 2.0. The virtual avatar received the tactile stimulus on its back through a virtual bar, with a trajectory that was either identical with the physical bar (condition with the FBI) or kept still (control condition without the FBI). Before the experiment, the precise position of the stool and the angle of the locators were carefully calibrated to ensure an accurate tracking of the HMD, controller, and tracker.

C. Experimental Setup and Protocols

Fig. 1a presents the experimental setup. A participant sat on the stool wearing the HMD and a 32-channel EEG cap, holding the same posture as the avatar in the virtual environment. An experimenter sat behind the participant, holding a physical bar equipped with a VIVE tracker. Tracking the physical bar's trajectory allowed the virtual bar to stroke the back of the virtual avatar with the same trajectory. In this case, the participant received a synchronous visuo-tactile stimulation, and the "OBE" FBI can be induced. The participants were instructed to concentrate on the virtual avatar. As a result, they received a tactile stimulation while seeing the virtual body being stroked in the same manner. The participants experienced the illusion of the tactile stimuli from the physical bar stroking their own back being produced by the virtual bar stroking the virtual body, which was observed by their eyes, resulting in a sense of ownership over the virtual avatar. The induction method employed herein was previously validated [34].

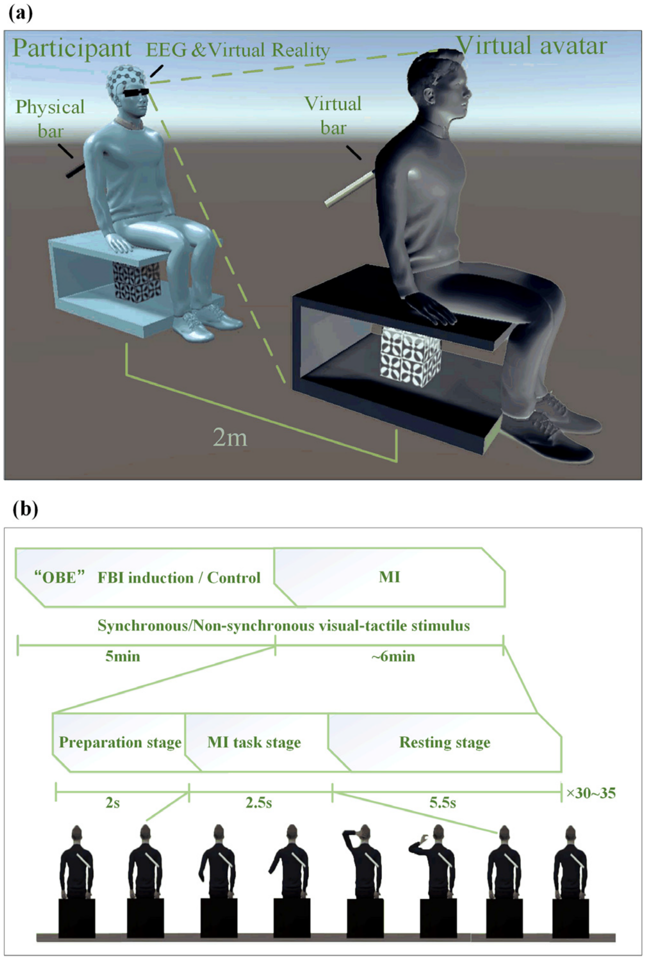

Fig. 1. Experimental setup (a) and protocols (b). (a) The participant sits on a stool wearing a 32-channel EEG cap and an immersive head-mounted display, maintaining a straight back with arms hanging naturally at their sides and legs joined. The virtual scene shows a life-size virtual avatar with the same posture sitting on a stool 2 m in front of the participant. An experimenter sits behind the participant with a physical bar held in his hand to deliver the tactile stimulus. A VIVE tracker was attached to the physical bar. Thi tracker tracked the physical bar's trajectory, such that a tempo-spatially congruent tactile stimulus can be delivered to the virtual avatar to induce the "OBE" FBI. (b) Enhanced MI (E-MI) paradigm consisting of an "OBE" FBI induction period, followed by an MI period and control MI (C-MI) paradigm consisting a control period, followed by an MI period. During the E-MI paradigm, the participants received a synchronous visuo-tactile stimulus through VR, whereas during the C-MI paradigm, they received non-synchronous visuo-tactile stimulus through VR.

Enhanced MI leads to amplified ERD [39] that can be evaluated using EEG [11]. A 32-channel EEG device (SynAmps amplifier, Neuroscan matched Ag-AgCl Quick-Cap, Compumedics Neuroscan) was used to record the EEG signals from the participants' scalps. Electrodes were placed according to the 10-20 international system (FP1, FP2, F7, F3, FZ, F4, F8, FT7, FC3, FCZ, FC4, FT8, T7, C3, CZ, C4, T8, TP7, CP3, CPZ, CP4, TP8, P7, P3, PZ, P4, P8, O1, OZ, O2, M1, and M2). The reference (REF) and ground (GND) channels were placed on the middle of the CZ and CPZ electrodes and the forehead, respectively. The signals were recorded using Curry7 software with a sampling rate of 1000 Hz. The bandwidth was set to 0.5–100 Hz. The electrode impedance was guaranteed to be below 5KΩ all throughout the experiment. All EEG data and markers were recorded for subsequent processing. Fig. 1b depicts the relevant procedures. Two paradigms were designed in this work, namely, Enhanced MI (E-MI) and Control MI (C-MI). For the E-MI paradigm, the "OBE" FBI was induced by a synchronous visuo-tactile stimulation with VR. The paradigm comprised two stages: the "OBE" FBI induction period and the MI period. During the "OBE" FBI induction period, the experimenter irregularly stroked the participants' back with a physical bar, while the virtual avatar was being stroked by a virtual bar with an identical trajectory. The C-MI paradigm was similar to the E-MI paradigm, except for the tactile stimulus applied to the participants and virtual avatar being non-synchronous (non-synchronous visuo-tactile stimulation). The virtual bar stroking the virtual avatar in the VR scene remained still, while the physical bar stroking the participant irregularly moved. The MI period was initiated following a 5 min control period. After the MI period of each paradigm, the experimenter asked the participant the yes/no question of whether or not he/she felt the virtual avatar as if it is his/her own body. This is a commonly used question for evaluating the subjective experience of the SOO [40].

During the MI period, the participants continued to receive a synchronous (E-MI paradigm) or non-synchronous (C-MI paradigm) visuo-tactile stimulation (i.e., the visuo-tactile stimulation was given throughout both the "OBE" FBI induction and MI periods). They were specifically asked to perform a MI task of the affected limb while being guided by the VR system (i.e., observing the virtual avatar doing the same movement). The movement chosen was hair combing, which is a common rehabilitation task [41], [42] frequently used to evaluate the motor ability of the upper extremity [43], [44], [45]. The MI period comprised 30 to 35 trials, each lasting 10 s. Each trial was divided into three stages, as illustrated in Fig. 1b.

- Preparation stage (−2 to 0 s): The participants were expected to relax, attend to the virtual body, and prepare for the MI task.
- MI task stage (0 to +2.5 s): The participants were asked to perform the MI task of the affected limb with visual guidance from the virtual scene.
- Resting stage (+2.5 to +8 s): The participants were given 5.5 s rest, during which the virtual avatar returns to the resting posture.

The two paradigms were conducted in a random order for each participant. The participants were instructed to concentrate on the task to minimize the influence of other conscious mental activities. A complete rest period of at least 15 min was provided between the two paradigms. The exact length of which was determined according to the subject's physical status.

The SOO induced by the synchronous visuo-tactile stimulus was previously shown to persist for up to 5 min after the end of the visuo-tactile stimulation [46]. Therefore, the SOO vanishes after a resting period of at least 15 min. To prevent fatigue effects on brain activities and remove the interference from the previous paradigm, particularly the induced FBI of the E-MI paradigm on the C-MI paradigm, the subjects were asked to remove the HMD and allowed to close their eyes, stand up, or take a walk in the corridor to fully relax their minds and bodies. Before starting the next condition, the experimenter also first verbally confirmed with the subject that he/she could not experience the SOO toward the virtual avatar and was made to prepare for the next condition.

D. Data Processing and Statistical Analysis

The enhanced MI can lead to an increase in ERD [10], [11], particularly in the α (8–13 Hz) and β (13–30 Hz) bands [47], [48]. Therefore, we focused our analysis on these two rhythms. We used EEGLAB [49] (version 2021.1) to analyze the EEG data. The EEG signals were first filtered using a band-pass filter with a low cutoff frequency of 0.1 Hz [50] and a high cutoff frequency of 40 Hz to remove the power interference and other noises while retaining the signals in the α and β bands [51], [52]. Subsequently, 6 s epochs were extracted for each trial, ranging from -2 to +4 s around the MI task onset, similar to that in previous studies [24], [53], [54]. Consequently, the epoch data included a baseline potential before the task began (−2 to 0 s), the brain potential during the MI task (0 to +2.5 s), and the post-MI potential (+2.5 to +4 s). Visual inspection was performed to discard trials with artifacts (e.g., caused by electrode cable movement or swallowing [54]) from further analysis. After which, an independent component analysis [53] was conducted to remove artifacts, such as eyeblink, head movement, and power line interference. Trials with an amplitude exceeding $\pm$ 120 μV were rejected. Finally, we re-referenced the recordings to the average signal recorded from the binaural mastoid leads.

1) Event-Related Spectral Perturbation Map: The baseline-normalized event-related spectral perturbation (ERSP) map (relative amplitude in %) of the ipsilesional hemisphere electrode was obtained for a qualitative analysis to explore the effect of the "OBE" FBI on the MI enhancement of the affected upper limb. We focused our analysis on the primary motor areas (M1), the activation of which was roughly detected by the EEG from channels C3/C4. This approach is a common choice for assessing the effectiveness of MI involving hand movements in healthy [25], [55] and stroke patients [56]. The C3/C4 channels were used to evaluate MI involving more complex upper limb tasks, such as wiping a table [57] and elbow rotation, among others [22]. We also focused our analysis on C3/C4, which are the most representative channels for the primary motor areas and commonly used for the upper limb rehabilitation assessment. For participants with affected left arm who performed the left upper limb task, we focused on the C4 electrode. Similarly, for participants with their right arm affected, we focused on the C3 electrode. Short-time Fourier transform (STFT) was applied to the EEG epoch data and averaged for all trials for each participant. The data during the preparation period were considered as the baseline. We normalized the average STFT for each participant by subtracting and dividing by the average power during the baseline period to obtain the relative ERD [58]. The baseline-normalized subject-level ERSPs were averaged over all subjects to obtain a group-level ERSP map for each paradigm. Our data (unpublished) revealed no significant difference between the ERD of the contralateral electrodes during MI of the left and right upper limbs in healthy subjects. Therefore, in this study, the data of the ipsilesional electrodes (C3/C4) during MI of the affected limb were averaged for all 13 subjects to obtain a group-level ERSP map.

We further compared the brain activation during MI between the two paradigms by obtaining group-level ERD curves within the α and β bands. More specifically, the mean and the standard deviation of the normalized power change within a specific band at each time point were calculated from the group-level ERSP map. The STFTs for each paradigm and channel were calculated and averaged across trials. The resulting values during the MI task stage within the α/β band were averaged and baseline-normalized to plot the group level topographical maps for each paradigm.

2) Peak ERD Amplitude and Statistical Analysis: We quantitatively compared the brain activations of the motor system between the two paradigms by calculating the peak ERD amplitudes through a well-established method [58]. For this analysis, we focused on the C3/C4 channel because they were the most illustrative when the upper limb movement was involved [25], [55]. The STFTs were calculated over either the C3 or C4 channel and averaged across trials to obtain the subject-level ERSP map, which was then baseline normalized. The values in the baseline-normalized subject-level ERSP map within an α or β band were averaged at each time point to obtain the relative ERD curves for these two rhythms at the subject level. Each curve was smoothed. The lowest peak was regarded as the peak ERD amplitude within the specific band for a particular participant and paradigm.

The peak ERD amplitudes in the α and β bands were extracted from both the ipsilesional and contralesional channels (C3/C4) during MI for both the E-MI and C-MI paradigms. The peak ERD amplitudes were presented in the form of scatter plots. A statistical analysis was performed to compare the ipsilesional and contralesional sides. The mean value and the mean standard error of the peak ERD amplitudes in the α and β bands were calculated for each paradigm, as well. The Shapiro-Wilk normality test was first performed on the peak ERD amplitudes. At normally distributed data, paired-sample t-tests were conducted to compare the E-MI and C-MI paradigms for the ipsilesional and contralesional channels; otherwise, the Wilcoxon signed-rank tests were performed. All statistical tests were conducted using SPSS 26.0 (IBM Corporation). The significance level of was set to 0.05.

III. RESULTS

With regard to the participants' responses to the question evaluating the subjective experience of the SOO, all participants provided positive responses after the E-MI paradigm. Therefore, the subjective experience of the SOO was successfully elicited for all participants under the E-MI paradigm using the synchronous visuo-tactile stimulation. In contrast, only three participants had positive responses after the C-MI paradigm.

A. Group-Level ERSP Maps and Topographical Maps

Fig. 2 illustrates the group-level ERSP maps of the C3/C4 electrodes on the ipsilesional hemisphere for the E-MI and C-MI paradigms. The vertical red and yellow lines indicate the start and end of the MI task, respectively. The horizontal white dashed lines denote 8, 13, and 30 Hz. The dark blue color indicates stronger ERDs corresponding to a larger power decrease. A visual inspection revealed a stronger ERD for the E-MI paradigm compared to the C-MI paradigm. Therefore, the MI task of the affected upper limb resulted in a stronger motor system activation when the "OBE" FBI was induced.

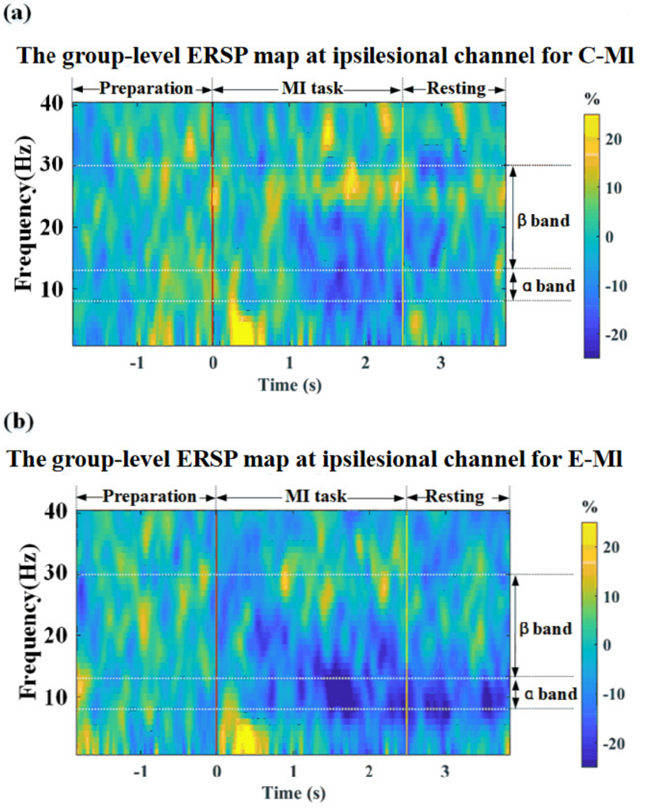

Fig. 2. Group-level ERSP maps at the ipsilesional channel for (a) C-MI and (b) E-MI. These maps illustrate the relative amplitudes (%) for each paradigm. The horizontal dashed white lines represent 8, 13, and 30 Hz. The vertical red and yellow lines represent the start and end of the MI task stage, respectively. The dark blue color corresponds to the negative relative amplitude and indicates a stronger ERD. The STFT for each trial for each participant was first averaged and baseline normalized. The resulting subject-level ERSPs were then averaged to obtain the group-level ERSP maps for each paradigm.

The group-level ERD time courses obtained from the C3/C4 electrodes on the ipsilesional hemisphere in both the α and β bands were further compared between the paradigms (Fig. 3). The temporal change of the mean and the standard deviation of the ERD value is shown. During the MI task period, the amplitude of the mean ERD curves (red and orange curves) below the dashed line indicates the ERD occurrence. A stronger ERD can also be observed for the E-MI paradigm compared to the C-MI paradigm in both rhythms. The orange line was below the red line in Fig. 3. The subject-level topological maps were averaged over participants with left and right hemisphere lesions, respectively, within each band. Fig. 4 displays the averaged topological maps within the α and β bands for each paradigm for patients with left and right hemisphere lesions. The blue areas correspond to a stronger ERD. The topological maps confirmed a stronger ERD for E-MI when compared to C-MI within both the α and β bands, regardless of the affected sides. The ERD calculated within the α band was stronger than that within the β band for the E-MI paradigm. Moreover, ERD was observed for both sides for the E-MI paradigm, indicating a bilateral motor system activation.

B. Peak ERD Amplitude and Statistical Analysis

The ERD amplitudes from the C3/C4 electrodes of the ipsilesional and contralesional sides in the α and β bands were extracted during the MI task stage. The subject-level peak ERD amplitudes within the α and β bands calculated

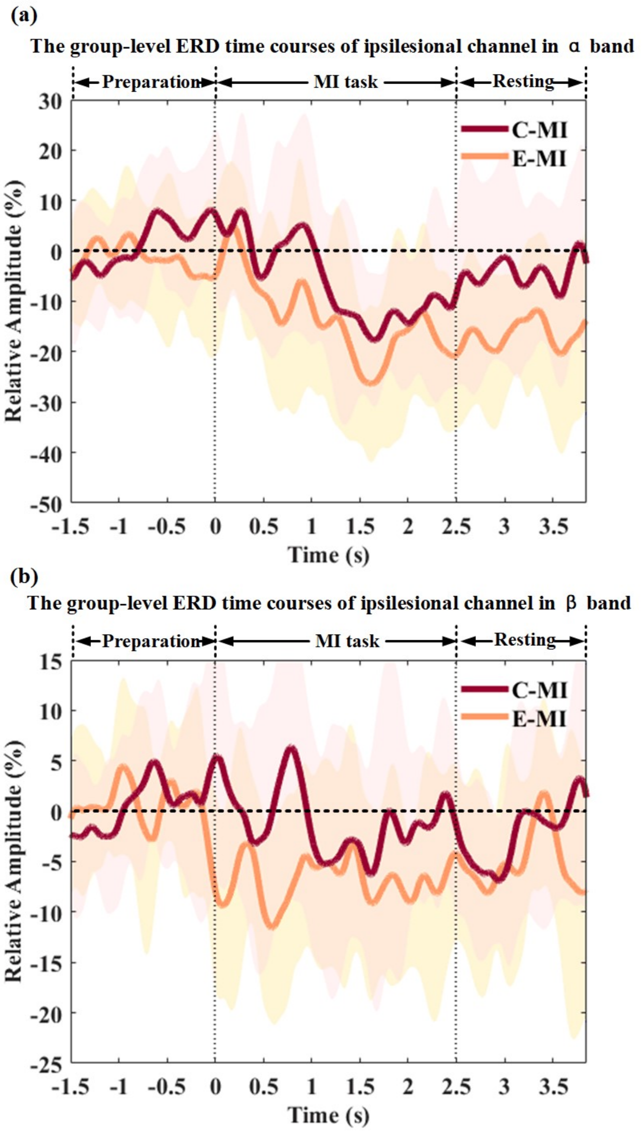

Fig. 3. Comparison of the group-level ERD (relative amplitude in %) time courses from the ipsilesional channel between the C-MI and E-MI paradigms within the (a) α and (b) β bands. The two vertical black lines represent the start and end of the MI task stage, respectively. The dark red curve indicates the mean ERD for the C-MI paradigm, and the light red curves indicate its ± standard deviation. The orange curve denotes the mean ERD curve for the E-MI paradigm, and the light yellow curves depict its ± standard deviation. The horizontal dashed line indicates a 0 vertical coordinate. The amplitudes below the line indicates the ERD occurrence.

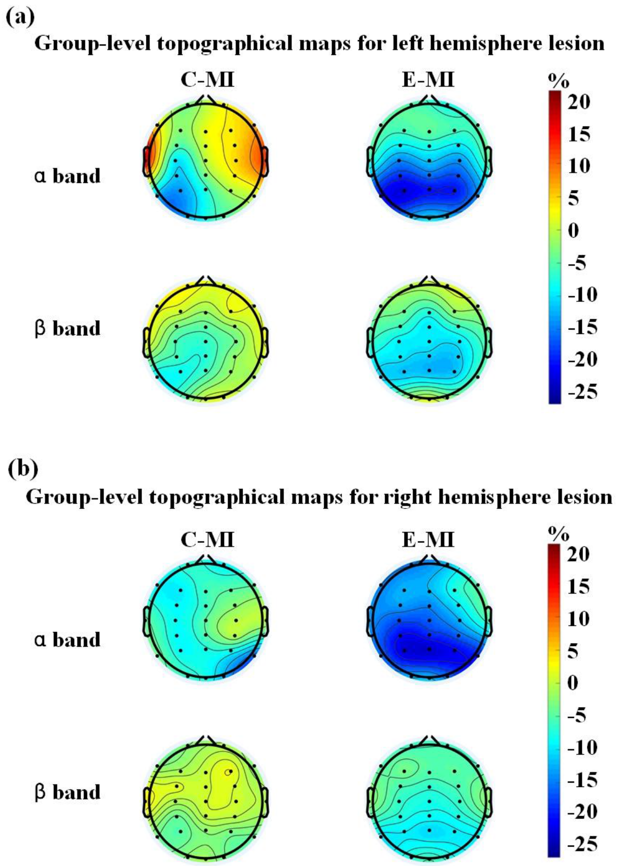

Fig. 4. Group-level topographical maps of the ERSP (relative amplitude %) in the α and β bands of the C-MI and E-MI paradigms during MI for patients with (a) left and (b) right hemisphere lesions. The dark blue color corresponds to a negative relative amplitude and represents a stronger ERD. We first calculated the mean ERSP maps for each participant and each channel by averaging the STFTs of a participant across all trials. We then averaged the ERDs during the MI task stage in the α and β bands for each participant and each individual channel based on the subject-level topographical maps obtained. Finally, they were averaged and baseline normalized to obtain the topographical maps for the C-MI and E-MI paradigms at the group level.

from the ipsilesional or contralesional channel for the E-MI paradigm were plotted with respect to that for the C-MI paradigm (Fig. 5). Each dot represents the peak ERD in the corresponding band for one subject in both conditions. The dashed dark line indicates equal peak ERD amplitudes between the two paradigms. The dots above the line represent a stronger ERD for the E-MI paradigm compared to the C-MI paradigm for this particular patient. In Fig. 5, most patients showed a stronger ERD for the E-MI paradigm for both ipsilesional and contralesional channels. Another observation was that the α rhythm showed a stronger ERD when compared to the β rhythm for both paradigms and sides, that is, the green squares were located in the upper right, and the gray dots were mostly distributed in the lower left part. More specifically, for the ipsilesional channel, 11 out of 13 patients exhibited a stronger ERD for E-MI in the α and β bands. For the contralesional channel, 12 patients had a stronger ERD for E-MI in the α band, whereas 10 had a stronger ERD for E-MI in the β band.

Statistical analyses of the peak ERD amplitudes were performed to compare the two paradigms (Table I). The Shapiro-Wilk normality test showed normally distributed values. For the ipsilesional hemisphere, a paired-sample t-test showed that the ERD peak amplitude in the E-MI paradigm was significantly larger than that in the C-MI paradigm in both the α (mean difference 8.69%, $t(12) = 3.076$, $p = 0.01$, $d = 0.829$) and β (mean difference 4.33%, $t(12) = 2.273$, $p = 0.042$, $d = 0.630$) bands. With regard to the contralesional hemisphere, the results were similar, that is, the peak ERD amplitudes for the E-MI paradigm were significantly larger than those in the C-MI paradigm in both

TABLE I

Peak ERD Amplitudes in the α and β Bands of the C3/C4 Electrodes on the Ipsilesional and Contralesional Hemispheres During the MI Task of the Affected Upper Limb, Given as the Mean ± Mean Standard Error (%), ** and * Denote Significance at the p < 0.01 and p < 0.05 Levels, Respectively

Frequency band	Paradigm	E-MI	C-MI	Paired-sample t-test	
				T value	P value
α	Ipsilesional	-40.09 ± 2.44	-31.40 ± 2.58	3.076	0.01**
	Contralesional	-42.58 ± 3.02	-30.37 ± 3.05	3.952	0.002**
β	Ipsilesional	-22.11 ± 1.59	-17.78 ± 1.50	2.273	0.042*
	Contralesional	-22.48 ± 1.67	-15.48 ± 1.95	4.167	0.001**

the α (mean difference 12.21%, t (12) = 3.952, p = 0.002, d = 1.096) and β (mean difference 6.99%, t (12) = 4.167, p = 0.001, d = 1.156) bands. Fig. 6 illustrates the statistical analysis results as boxplots, with the data distribution shown on the right side of each box.

We further compared the peak ERD amplitudes on the C3/C4 electrodes between the ipsilesional and contralesional hemispheres through a paired-sample t-test. The results showed no significant difference in the peak ERD amplitude in neither the α (mean difference 2.48%, t (12) = 1.105, p = 0.291, d = 0.307) nor β (mean difference 0.36%, t (12) = 0.259, p = 0.761, d = 0.072) band between the ipsilesional and contralesional hemispheres for the E-MI paradigm. Similarly, no significant difference was found in the peak ERD amplitude in the α (mean difference −1.03%, t (12) = −0.312, p = 0.800, d = 0.092) and β (mean difference -2.30%, t (12) = −1.59, p = 0.138, d = 0.441) bands between the ipsilesional and contralesional hemispheres in the C-MI paradigm.

IV. DISCUSSION

In this study, we proposed to enhance 3PP virtual rehabilitation training in stroke patients by eliciting the sense of body ownership through inducing the "OBE" FBI illusion. Body ownership is critical for virtual rehabilitation training [31], but is underrated in existing virtual training paradigms from the 3PP. The effectiveness of the proposed paradigm was evaluated herein in a motor imagery scenario. As widely acknowledged, enhanced MI results in amplified ERD [24]. Therefore, we recorded EEG signals and compared the ERD strengths between conditions when patients were doing the MI task of the affected upper limb with and without having an induced "OBE" FBI. The illusion was induced by a validated approach using a synchronous visuo-tactile stimulation [34]. Previous studies showed that ERD is also present in the ipsilateral brain during MI [59], [60], [61]. Similarly, our results implied a bilateral brain activation of both α and β rhythms of the motor system when stroke patients with an affected upper limb did the MI task. The activation was stronger when the FBI was induced. We attributed the elevated brain activities to the SOO over the virtual avatar produced by the induced "OBE" full-body illusion. The MI training with the SOO can more effectively activate the sensorimotor cortex, further facilitating the motor recovery [62]. Note that all participants reported subjective experience of the SOO during the E-MI paradigm, and some self-reported it was easier to perform the MI task with the affected upper limb while experiencing the SOO. Some also stated that it felt like they were sitting behind themselves and watching themselves perform the task.

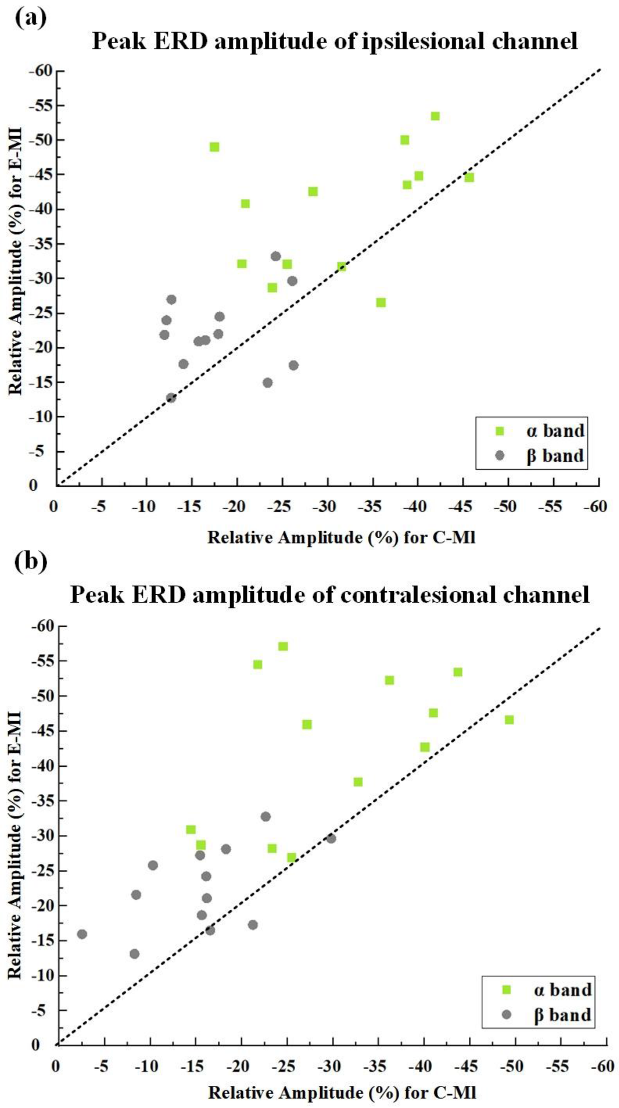

Fig. 5. Peak ERD amplitudes in the α and β bands for E-MI with respect to C-MI for each participant calculated from the (a) ipsilesional and (b) contralesional channels. The dark dashed line represents the equal ERD for E-MI and C-MI. The dots above the dark dashed line indicate a stronger ERD for E-MI compared to C-MI for this participant within a particular frequency band. The green squares correspond to the α band, while the gray dots correspond to the β band.

The results demonstrated that the proposed E-MI paradigm results in the power decrease in both α (8–13 Hz) and

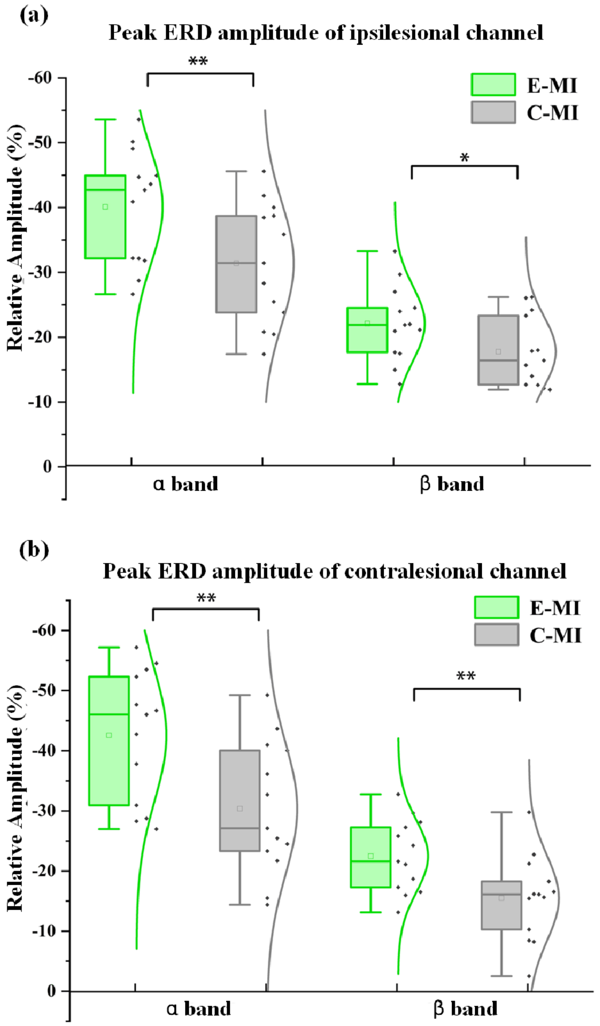

Fig. 6. Comparison of the peak ERD amplitudes between the E-MI and C-MI paradigms in both the α and β bands calculated from the (a) ipsilesional and (b) contralesional channels. The average and baseline normalized ERSP map showing the relative ERD (%) (i.e., percentage of power decrease) was calculated over the ipsilesional and contralesional channels for each participant. The relative ERDs for each participant within the α or β band were averaged at each time point, resulting in two relative ERD curves for these two frequency bands during the MI task stage. Each curve was smoothed. The peak ERD amplitude was obtained as the lowest peak of the smoothed relative ERD curve. The boxplots show the first quartile, median, and third quartile and 1.5 times the interquartile range for both the upper and lower box ends. The normal curve on the right side of each box illustrates the distribution of the peak ERD amplitude, with each black dot representing individual data. ** and * denote significance at the $p < 0.01$ and $p < 0.05$ levels, respectively.

β (13–30 Hz) rhythms for the EEG signals recorded at C3 and C4 channels, which were closely related to the motor-related regions (i.e., primary motor area [56]). This power decrease indicated an event-related desynchronization phenomenon with a strength commonly used to evaluate the MI enhancement [6], [24], [25]. An amplified ERD corresponded to a stronger brain activation and indicated enhanced MI. The proposed E-MI paradigm, that is, doing the MI task with an induced "OBE" full-body illusion, resulted in a stronger ERD in both the α and β bands for stroke patients when compared to the C-MI paradigm. In addition, ERD within the α band was stronger than that within the β band. These results were consistent with those of previous studies [11], [63], [64], suggesting that the E-MI paradigm can lead to stronger brain activation and a potentially better rehabilitation efficiency. The α rhythm was related to several cerebral functions that range from sensorimotor processing to memory formation [65], [66]. The α ERD was reported to represent a cortical activation state related to motor planning or preparation [11]. Compared to healthy individuals, stroke patients exhibited lower α band activation when performing visual guided MI tasks [67], [68]. This weaker α ERD in stroke patients was related to their cognitive and motor dysfunction [69]. Thus, the increased activation of the α rhythms for the E-MI paradigm might reflect an enhanced motor neuron activity and can potentially promote the motor function recovery for stroke patients [70]. β rhythms localized to the primary motor cortex [71]. The sensorimotor β oscillatory activity was recognized as a necessary element for voluntary movement [72]. Its activation was closely related to cortical motor processes [51] and movement initiation [73]. The abnormal β activity in patients may lead to motor retardation and difficulty for movement initiation [72]. The C3/C4 electrodes close to the primary motor area in the proposed E-MI condition showed a stronger β rhythm activation, which may help stroke patients with motor dysfunction to recover the movement initiation function and contribute to the motor function restoration.

Similarly, the topographical maps showed that MI led to a bilateral ERD with stronger brain activations in the contralesional hemisphere. With the "OBE" full-body illusion, the ERD signals were significantly amplified for both sides of the sensorimotor area. However, no significant difference in the peak ERD amplitudes between the ipsilesional and contralesional hemispheres for neither α nor β rhythms was found. This can be attributed to the compensation effect of the contralesional hemisphere in stroke patients with a unilateral motor cortex damage [74], [75]. Another phenomenon that is worth noting is that, apart from the C3/C4 channels, the FC3, FC4, CP3, and CP4 channels also exhibited an amplified ERD (Fig. 4) in the E-MI paradigm compared to the C-MI paradigm. These channels were related to motor-related regions (i.e., supplementary motor area [52] and somatosensory association cortex [76]). Note that the topographical ERSP maps demonstrated stronger ERDs at the CP3/CP4 electrodes compared to the C3/C4 electrodes. Following the same data analysis procedure, similar conclusions can be drawn from the CP3/CP4 channels. However, we did not choose the most active channels. We instead selected the channels that were the most representative for the upper limb motor function evaluation (i.e., C3/C4) [25], [55], [56]. They were used to evaluate the upper limb function, from simple hand movements to more complex ones involving the wrist, elbow, and arm [22]. This study primarily aimed to show the potential of the proposed paradigm in upper limb rehabilitation. Our results supported our claim by showing that the proposed paradigm can elicit a higher activation of the primary motor cortex on both group levels and on most individual patients, even though stroke patients exhibit diverse brain infarction areas in the contralateral hemisphere.

The group-level ERD time courses in the ipsilesional channel within the β band looked less distinct. This was attributed to the large variance in the arrival time of the peak ERD amplitude across subjects, as also revealed in another study involving the hand MI task [24]. Correspondingly, the resulting average peaks were weakened when averaging the ERD time courses across the subjects. The ERD during the MI period did not exceed much compared to that during the resting period because the brain activation during the former period persisted for a while after finishing the MI task. This phenomenon was also observed in previous studies involving the hand MI task [55], [77].

We induced the "OBE" full-body illusion in stroke patients through a synchronous visuo-tactile stimulation, similar to that in previous studies [34], [35]. As widely acknowledged, this illusion is caused by the abnormal integration of visual, tactile, motor, and vestibular inputs. A temporally synchronized visuo-tactile stimulus can induce the "OBE" full-body illusion and produce the SOO over a life-sized avatar in front of the participant from the 3PP [34]. The tactile stimulus of the virtual body was usually provided by immersive VR devices temporally synchronized with the tactile stimulus delivered to the physical body. The participants integrated the multisensory information synchronized from the real body and the virtual avatar. This integration can break the body representation and form a new sense of ownership to the virtual avatar in the field of view. Stroke patients experienced embodiment and presence similar to the healthy [31]. Therefore, the multisensory integration in stroke patients may remain intact or at least partially preserved, providing the basis for a successful induction of such an illusion in stroke patients [31], [38]. Studies also showed that the body ownership of moving objects can be induced on motionless participants [78], [79]. Therefore, in the E-MI paradigm, although the participant sat still on the stool without any overt movement, he/she could still have the SOO over the virtual avatar doing the movement. Studies further demonstrated that individuals tend to integrate the tactile stimuli with the delayed visual feedback during repetitive movements, which can result in an illusive perception of synchrony between the visual and tactile stimuli [80]. To avoid this, we chose to keep the physical bar still instead of giving a temporal shifted stroke trajectory for the control paradigm. Another motivation behind this choice was the exclusion of the possibility of the brain activations being caused by the tactile input.

Previous studies attempted to enhance the rehabilitation effectiveness in stroke patients by inducing the SOO [81]. By seeing a life-sized and gender-matched virtual avatar walking forward from the 1PP, the participants improved gait and balance after training [31]. However, seeing that from the 3PP did not. The authors argued that the participants experienced the SOO to the virtual avatar by simply observing the virtual avatar from the 1PP. They did not experience this while observing from the 3PP. The absence of the SOO was identified as a critical factor for the rehabilitation outcome. The author explained the promoting effect of the SOO on rehabilitation by internal model mechanisms. Internal model mechanisms [31] presented two internal models, that is, a forward model that predicts the body state of a performed movement and an inverse model that infers the motor commands for reaching a certain body state. Internal models for stroke patients can be damaged. For patients with motor deficits, the forward model is more likely to be impaired, while the inverse model remains functioning [31]. When the patients experienced the SOO over the virtual avatar, the sensorimotor system can regard the body state of the virtual avatar as their own and infer the motor commands for reaching certain body states. The training repeating this process can potentially restore the forward model functioning and facilitate the motor recovery. As a precondition of this theory, stroke patients can experience the SOO to the virtual avatar, which can indeed be met according to a previous study. This study shows that, albeit less intensively, stroke patients are competent to experience embodiment and presence in both the 1PP and 3PP scenarios [82]. In view of this, we attempt to promote motor functioning restoration with the 3PP training by inducing the SOO to a 3PP avatar. This is particularly important for rehabilitation when movements out of the field of view from the 1PP are involved.

For the three participants who self-reported experiencing the SOO after the C-MI paradigm, we individually investigated their peak ERD amplitudes for both conditions. Table II shows that they exhibit similar or even stronger ERDs in the α band on both sides for the C-MI compared to the E-MI paradigm. Similar ERDs in the β band between C-MI and E-MI were also found on the ipsilesional side for these participants. This was not surprising and did not conflict with our claim. It actually even partially supported the rationale underlying our study, that is, eliciting a strong SOO would enhance 3PP MI. Here, we proposed achieving this through a synchronous visuo-tactile stimulus previously validated to be effective [38]. Our experiment demonstrated that this method can indeed elicit the SOO to the virtual avatar for most participants, and the SOO elicitation further enhanced the 3PP MI. It is true that it seems easier for some patients to experience the SOO due to individual differences in the visuo-tactile functional integration. For these patients, the synchronous visuo-tactile stimulus seems unnecessary. However, the rationale underlying the study still holds, and the proposed paradigm is effective for most patients.

In this study, we did not differentiate patients with lesion in the left and right hemispheres. We instead averaged the data of the ipsilesional (contralateral) side (C4 for patients with lesion on the right side or C3 for patients with lesion on the left side) during MI of the affected limb. This can be justified from two aspects. First, this averaging approach was also performed in previous MI studies in stroke patients [56], [83]. Second, we found no significant difference in the ERD amplitudes in the contralateral side while performing the left (C4 electrode) and right (C3 electrode) upper limb MI tasks for the healthy participants (unpublished data). More specifically, we recruited 31 right-handed healthy participants and asked them to perform the MI tasks under both the E-MI and C-MI conditions, with both left and right upper limbs. Paired

TABLE II

PEAK ERD AMPLITUDES IN THE α AND β BANDS OF THE C3/C4 ELECTRODES ON THE IPSILESIONAL AND CONTRALESIONAL HEMISPHERES DURING THE MI TASK OF THE AFFECTED UPPER LIMB FOR THE THREE PARTICIPANTS WHO EXHIBITED A POSITIVE RESPONSE AFTER THE C-MI PARADIGM, GIVEN AS(%)

	α band			
	Ipsilesional		Contralesional	
Sub ID	E-MI	C-MI	E-MI	C-MI
7	-44.72	-45.59	-46.70	-49.28
11	-26.65	-35.84	-28.75	-15.51
12	-44.94	-40.02	-42.76	-40.04

	β band			
	Ipsilesional		Contralesional	
Sub ID	E-MI	C-MI	E-MI	C-MI
7	-17.68	-14.01	-25.82	-10.27
11	-21.14	-16.43	-18.68	-15.63
12	-29.69	-26.06	-28.12	-18.28

t-tests were performed to examine the effect of body sides on the ERDs. The results showed no significant difference in the peak ERD amplitude in both the α (mean difference -1.80%, t (30) $= -1.367$, p $= 0.182$, d $= -0.246$) and β (mean difference -1.47%, t (30) $= -1.189$, p $= 0.244$, d $= -0.214$) bands between the contralateral hemisphere while the left and right upper limb MI were being performed for the E-MI paradigm. Similarly, no significant difference in the peak ERD amplitude was found in both the α (mean difference 0.19%, t (30) $= 0.142$, p $= 0.888$, d $= 0.026$) and β (mean difference -1.51%, t (30) $= -1.196$, p $= 0.241$, d $= -0.215$) bands in the ipsilateral side while performing the left (C3 electrode) and right (C4 electrode) upper limb MI tasks. Similar results were obtained for the C-MI condition. In summary, it was rational to average the peak ERD amplitudes of the contralesional or ipsilesional side, regardless of the stroke location.

We chose hair combing as the MI task to perform for two reasons. First, it is a daily activity commonly used for upper limb rehabilitation [42] and is also frequently employed to evaluate the upper limb function [43], [44], [45]. Second, it involves large axial rotations of the humerus and large elbow flexions [43], as well as the back of the head. Therefore, it is out of the field of view of the 1PP and should be observed from the 3PP. The proposed paradigm can easily be extended to other movements.

Previous studies have demonstrated the utility of VR in stroke rehabilitation [23]. For stroke patients who can complete EEG experiments in the VR environment, the potential sensorimotor function may be preserved despite brain damage and motor deficits [84], [85]. The ERD is an important indicator for assessing the rehabilitation outcome of stroke patients [86]. Our results showed that the ERD of the sensorimotor area was significantly amplified when the MI task of the affected upper limb was performed with the “OBE” full-body illusion. The MI enhancement can further lead to a better rehabilitation outcome. We believe that the proposed paradigm with VR can be considered as an adjunctive therapy for stroke rehabilitation training. With the VR technology, immersive visual guidance can be provided to induce the “OBE” FBI for stroke patients and induce the SOO toward the virtual body [87]. This SOO led to the activation of the sensorimotor brain regions without actual movement. This may be of great help for stroke patients, especially for those unable to undergo conventional physical and occupational therapy due to motor deficits.

This study has limitations. First, we investigated the possibility of facilitating motor recovery through 3PP training in stroke patients with the “OBE” full-body illusion induction. Inducing the illusion in stroke patients led to MI enhancement of the affected upper limb, providing evidence for its potential in stroke rehabilitation. However, the long-term effect of the proposed paradigm on the rehabilitation outcome remains elusive due to the practical difficulties in patient recruitment and data collection. Second, we only controlled the proposed paradigm using C-MI with a non-synchronous visuo-tactile stimulus. Comparing this with action observation and pure MI will complement the current data and more comprehensively evaluate the MI enhancement of the proposed paradigm. However, most stroke patients failed to complete even just three of these conditions subject to their physical state and duration of attentional focus. Therefore, only two experimental conditions were practically allowed. We first discarded the pure MI, which was an easy decision to make for two reasons: controlling the E-MI with only pure MI cannot exclude the confounding factor of the visual stimulus; and many studies have already reported the MI enhancement of action observation [19], [26], [88]. Between the C-MI with a non-synchronous visuo-tactile stimulus and action observation, choosing action observation seems more straightforward and appropriate because participants can perceive the non-synchronous visuo-tactile stimulus as a disturbance. However, the primary claim of the study is that visual-guided 3PP MI can be enhanced by eliciting a strong sense of body ownership through the “OBE” full-body illusion. Even if the non-synchronous stimulus might lead to a weakened SOO compared to action observation, our data showed that a stronger SOO can lead to an enhanced MI, suggesting the feasibility of enhancing the 3PP MI by manipulating the SOO. A previous study also showed that the tactile stimulus can lead to a strengthened ERD in motor areas [89]. Choosing the C-MI with a non-synchronous visuo-tactile stimulus over action observation can control the confounding factor of the tactile stimulus. Some studies used a condition with temporal asynchrony between visual and tactile stimuli (i.e., the virtual bar moved with a consistent delay compared to the physical bar) [35]. Further investigations can be performed to compare the MI enhancement of the proposed paradigm with this control condition with temporal asynchrony.

The effect of eliciting the SOO to a 3PP virtual avatar on a cortical activity during MI in stroke patients was evaluated using the EEG. Other techniques (e.g., functional neuroimaging or motor function assessment methods) can be used to further evaluate the motor recovery after rehabilitation training with the proposed paradigm. More stroke patients can also be recruited to elaborate the effects of FBI induction on motor recovery for different patient groups (e.g., at different stroke stages, various lesion areas, and different levels of motor deficits). Movements involving the affected lower limb (i.e., gait and balance training) are worth investigating to provide a more comprehensive view on the potential of the proposed paradigm.

V. CONCLUSION

This study presented a novel approach of enhancing the MI training from the 3PP for stroke patients by producing a strong SOO through induction of the "OBE" FBI with VR to improve rehabilitation training. The effectiveness of this method was evaluated using the ERD calculated from the EEG signals. The results demonstrated that MI can significantly be enhanced when the participants experience an SOO over a virtual avatar from the 3PP by the "OBE" FBI induction. This study offers more possibilities for virtual rehabilitation in stroke patients and can further facilitate VR application in rehabilitation.

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