The Effects of Bilateral Phase-Dependent Closed-Loop Vibration Stimulation With Motor Imagery Paradigm

Wenbin Zhang, Aiguo Song, *Senior Member, IEEE*, Hong Zeng, *Member, IEEE*, Baoguo Xu, *Member, IEEE*, and Minmin Miao

***Abstract*— Vibration stimulation has been shown to have the potential to improve the activation pattern of unilateral motor imagery (MI) and to promote motor recovery. However, in the widely used left and right hand MI brain-computer interface (BCI) paradigm, the vibration stimuli cannot be directly applied to the imaginary side due to the spontaneity of imagery. In this study, we proposed a method of phase-dependent closed-loop vibration stimulation to be applied on both hands, and explored the effects of different vibration stimuli on the left and right hand MI-BCI. Eighteen healthy subjects were recruited and asked to perform, in sequence, MI tasks under three different conditions of vibratory feedback, which were no vibration stimulus (MI), phase-dependent closed-loop vibration stimulus (PDS), and continuous vibration stimulus (CS). Then the performance of the left and right hand MI-BCI and the patterns of brain oscillation were compared and analyzed under these different stimulation conditions. The results showed that vibration stimulation effectively boosted the activation of the sensorimotor cortex and enhanced the functional connectivity among sensorimotor-related brain regions during MI. The closed-loop stimulation evoked stronger event-related desynchronization patterns on the contralateral side of the imagined hand compared to continuous stimulation. There was a more obvious distinction between left hand task and right hand task. In addition, phase-dependent closed-loop vibration stimulation increased classification accuracy by approximately 7% (paired t-test, p=0.004, n=18) compared to MI alone, while continuous vibration stimulation only increased it by 4% (paired t-test, p=0.067, n=18). This result further demonstrated the effectiveness of the phase-dependent closed-loop vibration stimulation method in improving the overall performance of the MI paradigm and is expected to be further applied in areas such as stroke rehabilitation in the future.**

***Index Terms*— Brain-computer interfaces, closed-loop systems, motor imagery, phase-dependent, tactile stimulation.**

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I. Introduction

ELECTROENCEPHALOGRAM (EEG) is a signal commonly used in non-invasive brain-computer interface (BCI) systems, which can help people use brain activity to communicate and interact with external devices [1]. As an active BCI, the motor imagery (MI) paradigm is widely used in robotic control, neurorehabilitation training, and other fields. It allows users to modulate the alpha/beta rhythm of the sensorimotor cortex by imagining the movements of limbs such as hands or feet. Therefore generating patterns similar to the ones induced by active movements in the electromagnetic field. Such cortical activities are termed event-related (de)synchronizations (ERD/ERS) [2], [3], [4], [5]. In recent years, MI has also often been used to enhance motor learning and restore motor functions.

However, the factors such as individual differences, training time, and etc. strongly influence the decoding accuracy of MI-BCI [6] with about 15-30% of users unable to use MI-BCI (BCI-illiteracy) [7], [8]. These problems often affect the overall performance of motor imagery and significantly limit the application of the MI paradigm. Therefore, some studies have been conducted to improve the overall performance of the motor-imagery paradigm. In addition to the approaches of the signal processing algorithm improvements, the feature and electrode channel selection, and the multi-signal fusion methods (fNIRS, EMG, etc.) [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], the direction of combining multiple sensory stimuli with the MI paradigm to improve the overall BCI performance and creating a new fused BCI is also working on the right track [19]. This direction focuses on a hybrid BCI that combines MI paradigms with visual and haptic sensory stimuli or simultaneously induced multiple brain modalities (e.g., SSSEP, SSVEP) [20], [21], [22], [23], [24]. Among them, the haptic channel does not occupy the visual channel and thus retains the advantage of MI's spontaneity. It allows the subject to modulate brain activities autonomously so it is more practical, especially for users with vision deficits or in visually occupied scenarios.

There have been some preliminary studies on tactile-based BCI itself. Cincotti *et al.* [20] achieved a binary classification accuracy of 70% when first demonstrated the feasibility of the tactile-based paradigm through a selective sensory approach. The provision of tactile feedback was also shown to improve the sense of agency and enhance the decoding performance of MI-BCI. On this basis, the hybrid BCI of Yao *et al.* [25], combined selective sensation with the MI paradigm, effectively reduced the number of BCI-illiteracy. Similarly, Shu *et al.* [26] and Ahn *et al.* [27] also found that vibration stimulation can improve the overall performance of the MI paradigm, especially enhancing activation of motor-sensory cortex, improving decoding accuracy, and reducing training time. In addition to vibration stimulation, Gomez *et al.* [28] used a robot arm to drive the movement of imagery arm in order to close the sensorimotor loop by providing kinesthetic feedback, and it positively influenced MI decoding accuracy. Yi *et al.* [23] fused electrical stimulation with MI BCI. They improved classification accuracy by approximately 14% compared to MI alone through stimulus-evoked SSSEP. Although, the fusion of tactile stimulation and MI has the potential to improve overall performance of MI, current research tends to use open-loop stimulation with pre-set stimulation times, stimulation frequencies, and intensities. The studies of closed-loop stimulation systems adjusting stimulation to the real-time state of the brain are rare [29].

The use of neural oscillations as biomarkers for stimuli is still being investigated, where the phase of brain oscillations is an essential feature of neural processing. The different phases of brain oscillations represent different states of neuronal populations excitability, so it can be used as an indicator to assess brain excitability, guiding the delivery of stimulation [30], [31], [32]. Lindsley first suggested that brain states might be reflected by the phase of alpha oscillations in the form of phases [33]. Subsequently, an increasing number of studies have found that it has different effects when applying stimuli onto different phases of the brain [34], [35]. Mu rhythms are associated with phase-dependent inhibitory control, and neuronal spiking activity decreases during the positive peaks of local mu oscillations [36]. Ai *et al.* [37] found that the phase and amplitude of alpha oscillations affect tactile perception and that alpha peaks inhibit tactile perception. Zrenner *et al.* [38] found that negative peaks of sensorimotor mu rhythms represent a more responsive state than random phases and peaks. In addition, stimulation at a specific frequency can induce an increase in cortical rhythmic activity at the same frequency, resulting in a more regular and easier-to-capture EEG rhythm pattern [39], [40].

On this basis, we developed a phase-dependent closed-loop vibration stimulation system to improve the MI paradigm performance. We demonstrated the effectiveness of this system applying to a non-dominant hand in a previous study [41]. Tactile stimulation applied to the imagined side has been shown to boost the activation of the contralateral sensorimotor cortex, thereby improving MI performance. However, in the most widely used left and right hand MI paradigm, it is impossible to apply stimuli only to the imagined side because of the spontaneity of imagery. However, it is unclear to see the effect of MI when simultaneously applying tactile stimuli on both sides, and existing studies have also yielded mixed results [23], [25], [27], [42]. Our previous study found that when applying continuous vibration stimulation to either imagery or resting task of a non-dominant hand, it produced significant activation in contralateral sensorimotor areas. This has attenuating the difference in ERD patterns between the imagery task and the resting task, and affecting classification accuracy. In contrast, closed-loop vibration stimulation produced fewer adverse effects and enhanced overall MI performance more efficiently. This may also be valid for the left- and right-handed MI paradigm.

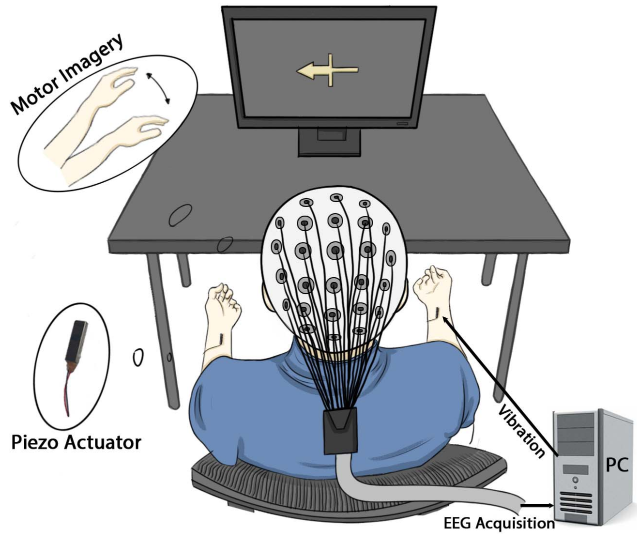

Fig. 1. The schematic of the experimental setup. The subjects sat comfortably in a chair with hands relaxed on the armrests, and performed left-hand or right-hand motor imagery tasks according to the arrows displayed on the screen. Two piezo tactors were fixed on the left and right wrists of the subjects, respectively, and vibration stimulation was applied according to the current task type. The tactors are driven by sound waves amplified by an audio amplifier.

The main contributions of this paper include: in order to further investigate the effect of phase-dependent closed-loop vibration stimulation on the overall performance of the motor imagery paradigm, we applied vibration stimulation to the median nerve of the left and right wrists simultaneously and set up three control experiments, namely, pure motor imagery (MI), continuous open-loop vibration stimuli (CS) and phase-dependent closed-loop vibration stimuli (PDS). The oscillation modes and time-frequency characteristics of the EEG were compared under different conditions using the event-related spectral perturbation (ERSP) and other methods. Inter-channel connectivity was assessed and analyzed by calculating phase-locked values (PLV). Using the common spatial pattern (CSP) algorithm for feature extraction and linear discriminative analysis (LDA) for classification to evaluate the overall performance of the left and right hand MI paradigm under different vibration stimulus conditions.

II. Methods

A. Subjects

Eighteen healthy subjects (13 males, 5 females, age range 22-33 years) participated in the experiment. All subjects had normal or corrected-to-normal vision. They were all healthy and had no known neurophysiological or musculoskeletal disease. None of the subjects have prior experience with MI BCIs. Before the experiment, everyone understood the basic procedures of the experiment and signed the informed consent form. However, they were not informed about when and what vibration stimulation would be applied and the purpose of the vibration stimuli to avoid psychological biases when performing imagery tasks. The study was given permission by the Ethics Committee of the First Affiliated Hospital of Nanjing Medical University (2020-SR-362).

B. EEG Recording and Phase-Tracking Approach

We used a 64-channel active electrode system (ActiCAP Systems, BrainProducts GmbH, Germany) to acquire continuous EEG signals. The sampling frequency was 1000 Hz, and the impedance of electrodes was kept below 10kΩ during the recordings. All the electrode channels were referenced to the channel FCz, and the channel FPz was served as the ground. We adopted an analog bandwidth filter with 0.1 Hz to 100 Hz and a notch filter with 50 Hz to the signals to attenuate interference. Before offline analysis, the automatic artifact removal (AAR) based on the SOBI algorithm [43] from the EEGLAB toolbox [44] was used to remove the artifacts caused by eye movements. And used the common average reference (CAR) algorithm to re-reference the signals.

To apply vibration stimuli at a specific phase of the alpha band, we used the real-time phase prediction algorithm used in our previous study. This fast Fourier transform (FFT) based algorithm, proposed by Farrokh *et al.* [45], obtained a relatively stable performance (PLV=0.71) in the previous study. During the experiment, we used MATLAB to acquire EEG signals in real time through TCP/IP protocol. In the PDS session, we extracted the last 300ms data of the C4 channel every 40ms starting from the 5th second of each trial and executed the following steps to forecast the phase of the current time point: First, a 10th order elliptical infinite impulse response (IIR) filter was used to filter the data to 8-12 Hz; second, the FFT of this data segment is calculated; third, the frequency and phase of the dominant component of the signal were calculated from the FFT; and finally, using a simple sine function to forecast the signal by using the calculated phase and frequency. According to previous experience, the stimulation of the alpha frequency band was delayed to offset the influence of system delay and other factors.

C. Tactile Stimulation

Vibration stimulation was provided by two piezo vibration actuators placed at the median nerves of the left and right wrists. These tactors utilize the properties of piezo-electric materials rather than the traditional electronic/magnetic motor design to produce the vibratory stimulus. Providing a faster response (less than 3ms), less noise, and a greater accuracy. The vibrator was taped on the median nerve of the subject's left and right wrist.

This study adopted two modes of vibration stimulation: continuous vibration stimulation and phase-dependent vibration stimulation. In order to stimulate the Pacinian and Meissner corpuscles simultaneously, and these two mechanoreceptors are sensitive to frequencies above 100 Hz and 20-50 Hz [46], we applied the continuous vibration stimuli constantly during the imagery period (5th-11th seconds of each trial). An electrical signal of 200 Hz sinusoidal carrier frequency modulated by 23 Hz sinusoidal frequency was generated using a computer soundcard and amplified using an audio amplifier in order to drive the actuators. The phase-dependent vibration stimulation determines when to trigger the vibration stimulus depending on the real-time phase predicted by the instantaneous phase prediction algorithm. Each triggered vibration at a frequency of 200Hz for 20ms. The stimulus was applied to the falling ($[5 \times \pi/6, 4 \times \pi/3]$) phase of the alpha oscillations in the C4 channel. To avoid repeated triggering or estimation errors, the interval between each stimulation must be greater than 80ms. In order for the subjects to feel the rhythm better, the amplitude of every third vibration stimulus is 50% higher than the first two ("tic-tic-toc" pattern [47]).

Before starting the experiment, each subject was asked to feel the intensity of the vibration at different amplitudes and to choose the intensity that they could clearly feel without affecting their imagination as the parameter for the experiment. Vibration amplitudes were controlled by the audio amplifier.

D. Experimental Procedure

The experimental scene is shown in Fig. 1. The subjects sat in a comfortable chair throughout the whole process. Their eyes were about one meter away from the monitor, and their hands were relaxed on the armrests of the chair. To avoid placebo effects, the piezo actuators were attached to the subjects' wrists from the beginning to the end of the experiment. The experiment was controlled by Psychtoolbox [48].

The experiment consisted of three sessions: motor imagery without stimulus (MI), motor imagery with phase-dependent vibration stimulus (PDS), and motor imagery with continuous vibration stimulus (CS). The subjects executed the three sessions in sequence. Fig. 2 illustrates the paradigm of a single trial in every session. The time structure of all sessions was the same as the imaginary task performed by the subjects, but the vibration applied were different.

At the beginning of each trial, a white cross was displayed on the screen, and the subjects could relax and rest for 4 seconds. At the fourth second, a white circle appeared in the middle of the cross and lasted 1s, reminding the subjects to pay attention as the imagining task was about to start. Within 5-11 seconds, left or right arrows randomly appeared on the cross, and the subjects performed the corresponding left-hand or right-hand MI tasks according to the direction of the arrow. In the end, the screen displayed the white cross again, and the subjects relax and rest before entering the subsequent trial. To minimize artifacts such as electrooculography, subjects were asked to avoid extra body movements such as blinking during the motor imagery tasks.

Each session contained two runs, and each run contained 40 trials, in which the left and right hand tasks were performed 20 times each in a random order. Each trial took 11 seconds,

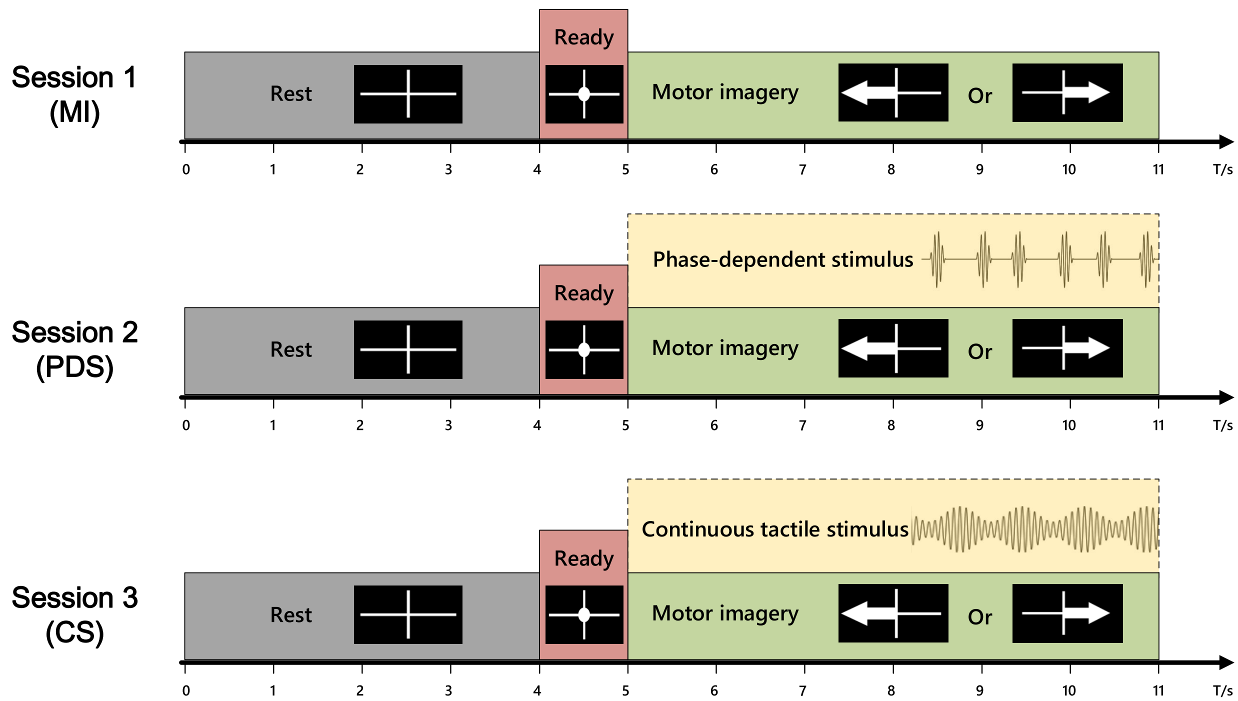

Fig. 2. Experimental procedure of the three sessions. Each session contains two runs, and each run consists of 40 trials. All the sessions shared the same time frame, and subjects performed a unified imagery task, the only difference being the timing and method of applying the vibration stimulus.

each run lasted about 7 minutes, and the subjects had a 5-10 minutes resting period after each run. In order to ensure that the subjects can correctly understand the requirements of the experimental tasks, so perform the motor imagery tasks better and avoid the influence of the proficiency in experimental results, each subject performed 20 trials of actual movement and 20 trials of MI before the start of the experiment.

E. Algorithms and Analysis Methods

In this study, we used custom-built MATLAB scripts and EEGLAB toolbox algorithms to analyze EEG data offline. Event-related spectral perturbation (ERSP) and ERS/ERD were used to evaluate the mean spectral power changes in time-frequency and spatial domains. We calculated ERSP and ERS/ERD in the alpha (8-12 Hz) and beta (13-30 Hz) bands, in order to evaluate the effect of vibration stimulation on MI in different frequency bands. The ERSP of n trials was calculated by the Eq. 1:

$$\mathrm{ERSP}(f,t)=\frac{1}{n}\sum_{k=1}^{n}\left(F_k(f,t)^2\right) \tag{1}$$

where n is the number of trials and $F_k(f,t)$ denotes the spectral estimation of the kth trial at frequency f and time t. The ERSP was computed in EEGLAB by calculating a short-time Fourier transform (STFT) every 200 ms with a Hanning-tapper. The reference interval was the 2th-3th second of each trial (2 seconds before the attention cue appeared). The topographical distributions of ERSP were computed by averaging the ERSP values of all electrodes within the specific frequency bands at 5-10 s. Representative electrodes C3 and C4 were chosen to calculate and demonstrate ERD/ERS changes during MI tasks.

The phase-locking value was used for measuring the phase synchronization information between pairs of signals, which can quantify the functional connectivity between different brain sites. It is calculated over the N-sample window as follows:

$$PLV=\left|\frac{1}{N}\sum_{t=0}^{N-1}e^{i\left(\varphi_x(t)-\varphi_y(t)\right)}\right| \tag{2}$$

where N represents the sample amount of each signal. $\varphi_x(t)-\varphi_y(t)$ stands for the instantaneous phase difference between each pair of EEG channels $(\boldsymbol{x},\boldsymbol{y})$ on time window t. The instantaneous phase is calculated by the Hilbert transform. The PLV ranges from 0-1, with 1 denoting complete phase synchronization and 0 denoting that the signals are completely desynchronized. We used a sliding window of 1 s to average the data during the imagery task to obtain a 63 × 63 PLV matrix. Furthermore, we investigated the local-scale synchronies of left and right M1 areas as these areas are considered as the primary cortical areas involved in the hand MI tasks. For the measurement of local-scale synchrony, four neighboring electrodes of C3 and C4 were combined to form a five-electrode group. Averaging four combinations of electrode pairs from five electrodes yielded the phase-locking value.

In addition to the time-frequency feature, classification accuracy is also a crucial indicator for the overall performance of MI-BCI. We used the bandpass filter to filter the raw data of all 63 channels to 8-30 Hz and extracted the 5th-10th second (5 s after the beginning of imagination) data of each trial for feature extraction and classification. To investigate the impact of vibration stimulation on the classification accuracy of the

MI paradigm, we use the traditional common spatial pattern (CSP) for spatial filtering and linear discriminative analysis (LDA) as a classifier, both were widely used in MI based BCI literature.

A 10-fold cross-validation strategy was used in the classification for statistical analysis. Each session contains 80 trials, randomly divided into ten sets of 8 trials. Nine of the ten sets were used for training the CSP filter and the LDA classifier, and the remainder was utilized for testing. This step was repeated ten times for a total of 80 outcomes. Finally, the average classification accuracy was taken as the final classification result.

III. Results

A. Comparison of Electrophysiological Features

Fig. 3 shows the average ERSP topographic maps for the three sessions across all subjects. From left to right are MI, CS, and PDS. The three frequency intervals selected are alpha rhythm (8-12 Hz), beta rhythm (13-30 Hz), and alpha-beta rhythm (8-30 Hz), corresponding to the first to the third column of each session in the figure. The first and second rows show the mean ERSP from the 5th to 10th second in the left and right-hand motor imagery tasks, respectively. As can be seen from the maps, the subjects produced a significant contralateral ERD in the alpha band in all sessions, while the activation pattern of the beta band was not obvious in MI sessions. Both CS and PDS significantly boosted ERD activation in the alpha and beta frequency bands compared to the MI task, but a more focused and deeper activation can be observed under PDS. In the CS task, activation was observed in more regions, including in the parietal and occipital lobes, but the patterns were less concentrated. In addition, the impact of vibration stimulation on motor imagery tasks was more pronounced in the left-hand imagery than in the right hand.

Fig. 4 shows the ERSP distributions from one representative subject (S6) across time-frequency (a) and spatial domains (b). In the time-frequency domain, the left and right sensorimotor cortex are represented by the C3 and C4 channels, respectively. This subject presented significant desynchronization in the contralateral hemisphere of the imagery hand under all tasks. Both tasks with additional vibrational stimulation produced significantly more activation in the beta band and higher frequency bands than in the MI task. The PDS task produced significantly stronger activation in the alpha and beta frequency bands on the contralateral side of the imagery hand, covering the widest range of frequency bands. The response time of activation under the three tasks were similar, and vibration stimulation did not significantly accelerate the rate of desynchronization generation. In contrast, the duration of activation showed different results. The PDS task produced the most persistent and stable alpha-beta activation in the contralateral brain region in both the left- and right-hand tasks, while the CS task did not significantly increase the duration of activation compared with MI. Notably, significant ipsilateral ERS was observed in both left- and right-hand imagery tasks without vibratory stimulation, while both CS and PDS tasks reduced ipsilateral ERS to a various degree. That is consistent with the results exhibited by the topographic map.

In the spatial domain, the enhancement of the ERD pattern by vibration stimulation can be clearly observed. While comparing to the CS task, the activation area of the PDS task is more concentrated, and the activation degree is the deepest. The MI and CS tasks produced more significant contralateral activation in the right-handed imagery task than the left-handed task. However, the PDS task was the opposite, phase-dependent vibration stimulation significantly enhanced the activation of the cortex near C4. No concentrated ERS can be seen from the topographic map, but the energy enhancement on the ipsilateral side can still be clearly observed. It can be seen that bilateral tactile stimulation can boost the activation of the motor-sensory cortex induced by motor imagery.

B. Phase Locking Value

Fig. 5 shows the grand averaged PLV values of the left- and right-handed tasks in the alpha and beta bands for different sessions in C3 and C4 local, respectively. The results show that the vibration stimuli generally enhanced the mean PLV values of the left and right motor sensory cortices in both alpha and beta bands, with the CS being mostly higher than the PDS in terms of mean values. There were significant differences between C3 local and C4 local within all the same frequency bands and tasks (paired t-test, $p<0.01$). In contrast, the differences between the left and right hand tasks were not significant under the same conditions and regions. Regarding mean values, there was almost no difference between the left and right hand tasks for CS, except for the C4 local in the beta band. In contrast, there were significant differences between the MI and PDS tasks, especially in the C4 local. That may be because bilaterally applied vibration stimuli significantly induced cortical activation on both sides. Vibratory stimuli elicited more pronounced changes in PLV values in the beta band compared to the alpha band because beta oscillations are particularly sensitive to somatosensory stimuli.

From the PLV matrix in Fig. 6, CS and PDS have more electrode pairs to obtain larger PLV values than MI. Vibration stimulation activated more brain regions in the alpha band. It can be seen that PDS has more synchronized nodes and the highest level of brain activation, with greater overall synchronization than MI and CS. In addition, the right-handed task produced slightly higher levels of synchrony than the left-handed task in the PDS, but the difference between the left- and right-handed tasks was not significant in the MI and CS.

C. Classification Performance

Fig. 7 illustrates the offline classification accuracy of all subjects in different conditions. The average classification accuracy of the three tasks was 63.6%, 67.4%, and 70.2%, respectively. Except for subjects S15 and S18, the addition of vibration stimulation effectively improved the classification accuracy of MI. Compared with MI, CS and PDS increased by approximately 4% (paired t-test, $p=0.067$) and 7% (paired t-test, $p=0.004$), respectively. This result demonstrated that

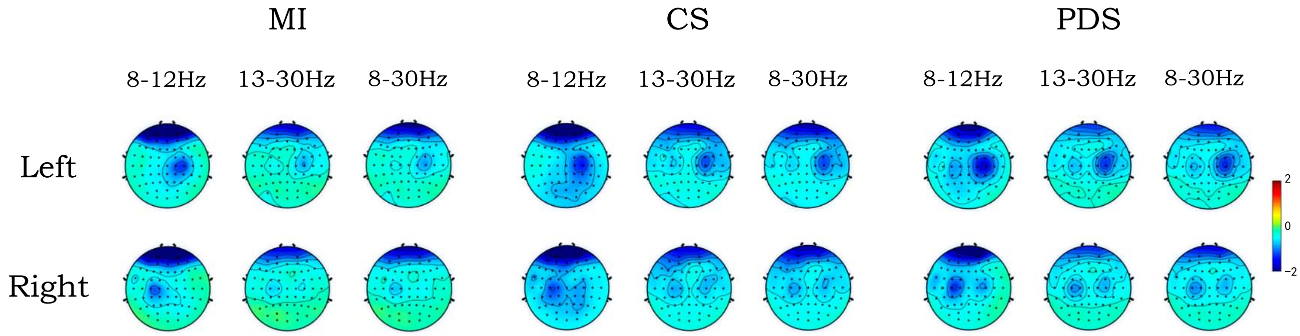

Fig. 3. Grand-averaged spatial distributions of ERSP patterns of all subjects for each class and frequency band. The upper and lower rows correspond to left-hand and right-hand MI tasks, respectively, and each column corresponds to three typical frequency ranges in different sessions.

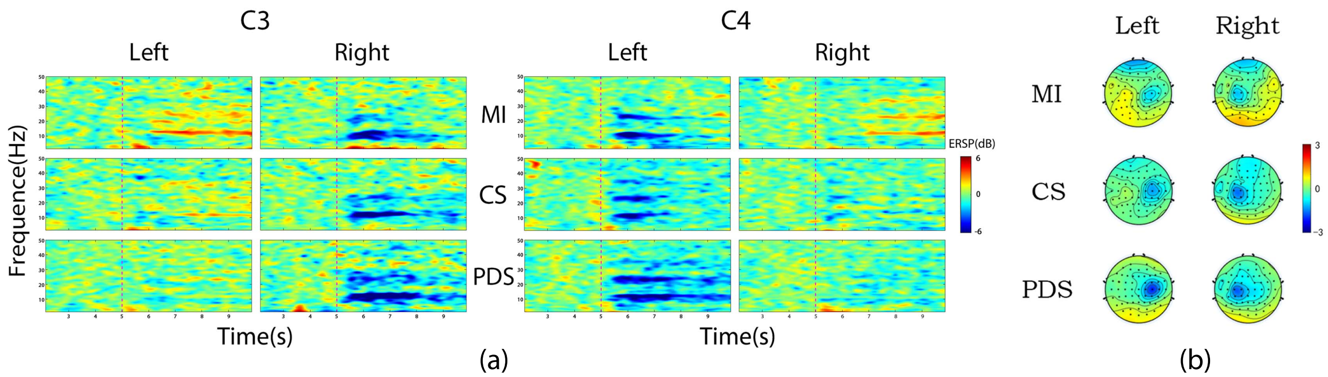

Fig. 4. The cortical activations in time-frequency (a) and spatial (b) domains for subject S6.

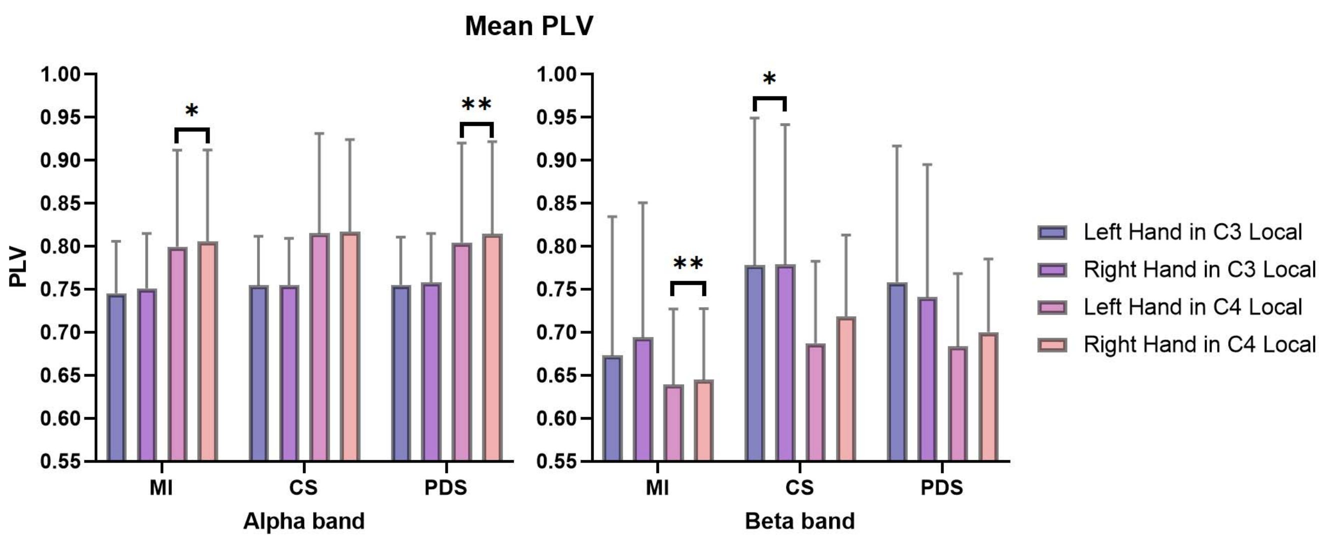

Fig. 5. Mean PLV values of different tasks in alpha and beta frequency bands in different brain regions. Only the values with significant differences in the same session are marked in the figure. The P values for each value combination are shown in Table. I. Where * represents $p<0.05$, ** represents $p<0.01$.

the phase-dependent closed-loop vibration stimulation significantly improved the performance of MI-BCI. Nine of the eighteen subjects achieved a 70% greater accuracy under the PDS task, while only five subjects achieved it under the MI task. Although the average classification accuracy of PDS was improved by about 3% compared to CS, no significant difference was observed between them (paired t-test, $p=0.074$). Compare to MI, seven subjects obtained lower accuracy in

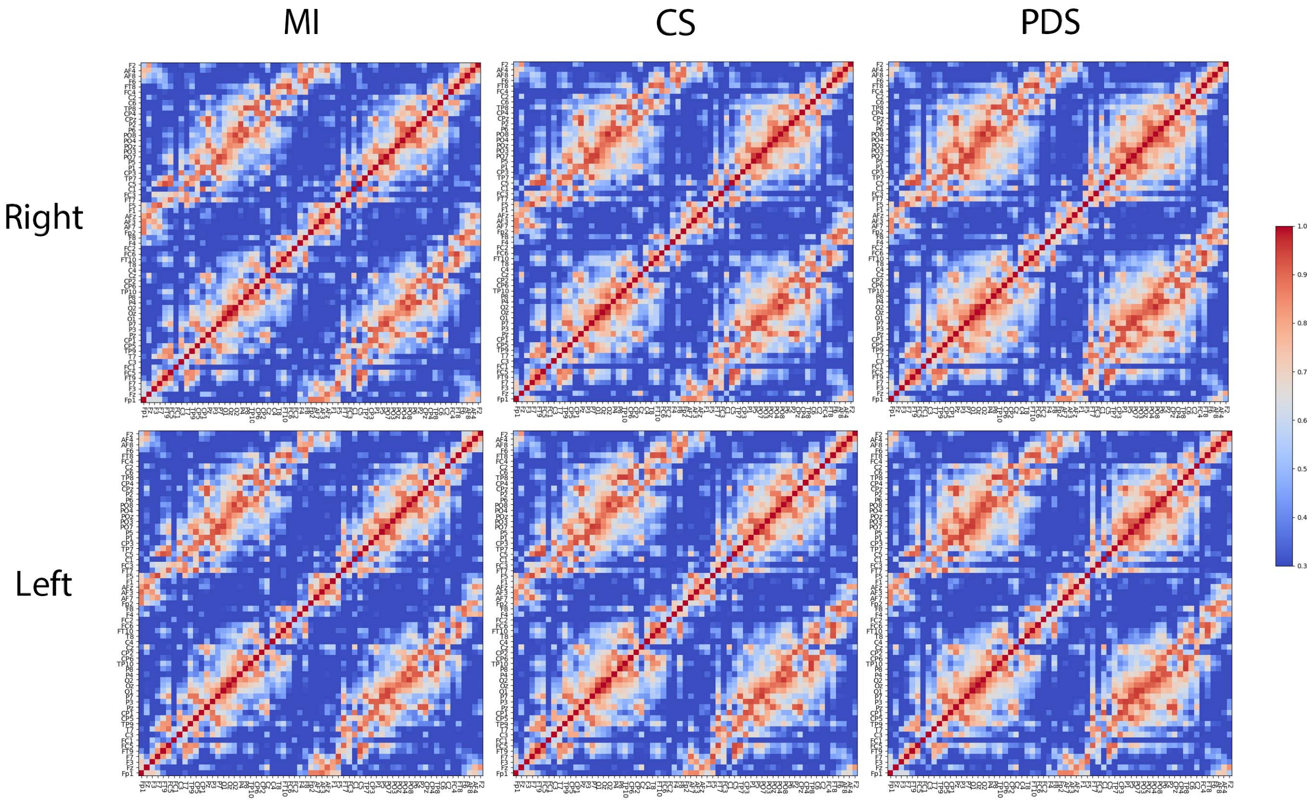

Fig. 6. Mean PLV matrix for all subjects with left and right MI for three sessions.

TABLE I
PAIRED T-TEST P-VALUE OF PLV BETWEEN DIFFERENT TASKS

Brain Region	P-value	MI-CS	MI-PDS	CS-PDS	MI-L-R	CS-L-R	PDS-L-R
C3 Local	Alpha-L	0.0538	**0.0236**	0.4435	0.0969	0.4743	0.2414
	Alpha-R	0.2637	0.0693	0.1838			
	Beta-L	**0.00001**	0.0827	**0.0016**	**0.0439**	0.2698	**0.0021**
	Beta-R	**0.0056**	**0.0028**	0.1577			
C4 Local	Alpha-L	0.157	**0.0062**	**0.0006**	0.2238	**0.0108**	0.3618
	Alpha-R	0.2944	**0.0035**	**0.0083**			
	Beta-L	**0.0246**	**0.0151**	0.3644	**0.0083**	0.248	0.3702
	Beta-R	**0.0009**	**0.00001**	0.4114			

CS, but only three did in PDS, indicating that although there are individual differences, closed-loop vibration stimulation showed a more stable and effective improvement in the overall performance of MI than continuous vibration stimulation.

IV. Discussion

This study investigated the effects of the overall MI performance with left and right hand when applying open- and closed-loop vibration stimuli on both sides; and assessed the subjects with their MI decoding rate, time-frequency features, and functional connectivity under different vibration stimuli. Unlike stimulation modalities such as TMS, which effect directly on the cerebral cortex, vibration stimulation creates sensory input via tactile receptors in the primary sensory-motor areas of the brain. Chatterjee *et al.* [19] found that when vibration stimulation applied on the ipsilateral side of the imagined hand, BCI accuracy could be significantly improved, with the left side showing significantly higher improvement than the right side. However, because MI is a spontaneous BCI, it is not possible to apply the vibration stimuli only on the imagined side, so the stimuli are often applied to both sides simultaneously.

From the available findings, it appears that directly applying of the vibratory stimulus to both sides does not significantly improve the overall performance on the left and right hand MI tasks. Because MI is a complex mental task, cortical activation due to the perception of tactile stimuli alone does not necessarily result in an immediate increase in classification accuracy [49]. In this study, the CS task significantly enhanced both bilateral motor-sensory cortical activation and

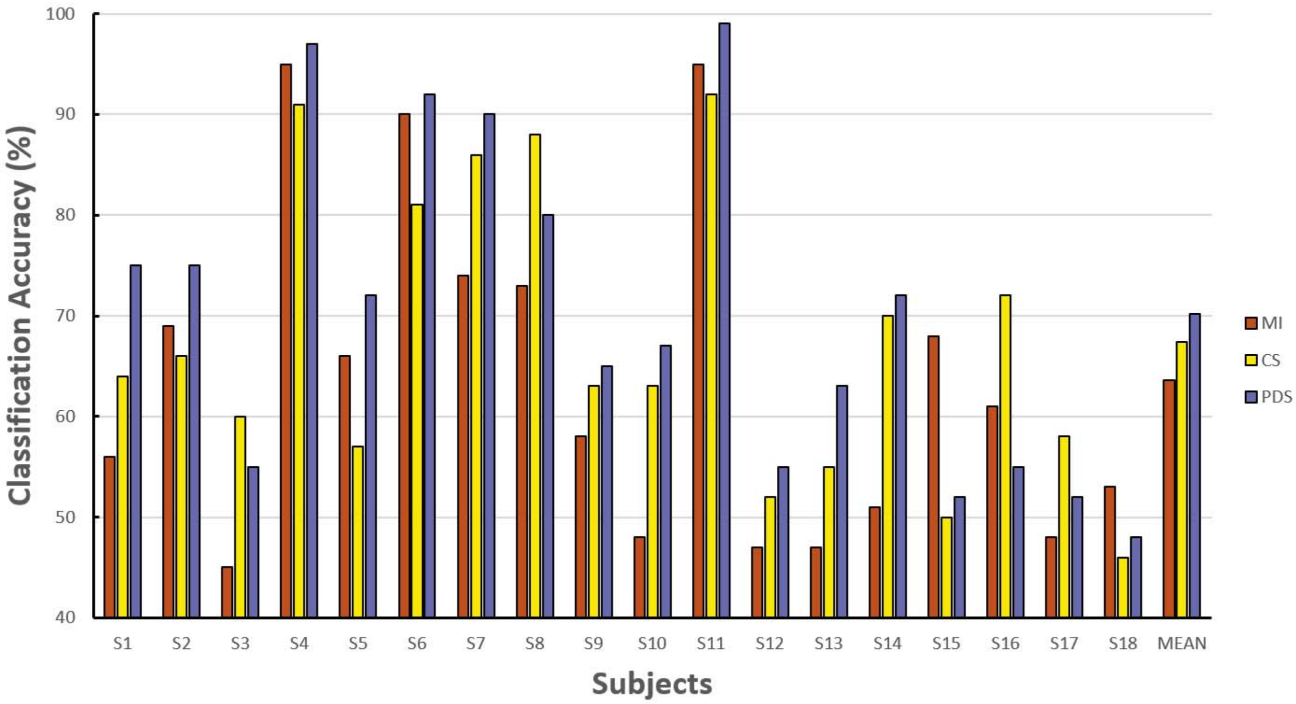

Fig. 7. Classification accuracies and mean accuracies in three conditions over 18 subjects.

the ERD pattern of MI, but did not significantly increase the classification accuracy. Similarly, Yi *et al.* [23] found no significant difference in classification accuracy between MI and combined electrical stimulation when using the ERD feature alone, but there was an increase of approximately 9% when using it with the SSSEP feature. In addition, the study used electrical stimulation, which was much stronger than vibration stimulation, suggesting that stimulus intensity does not determine the enhancement effect.

Because of the low task specificity of ERD, only considering ERD features can easily lead to a misidentification of the task [50]. Many studies have introduced SSSEP features alongside the bilateral stimuli [23], [29] or asked subjects to perform selective sensory tasks alongside the motor imagery [25], [27] to enhance overall MI performance. However, to induce a stable SSSEP, the amplitude and frequency of each subject and each stimulation position needed to be pre-tested, and the pre-work is complicated. Also, the lack of studies on the stability of SSSEP makes the validity of long-term use questionable [29]. The combination of selective sensation with MI provided good results because modulating the attentiveness towards vibratory stimuli can be translated into control commands. However, the superimposition of the tasks increases the complexity of the imagery task, this may interfere with subjects' imagination of limb movements. In contrast, the closed-loop vibration stimulation preserved the advantages of the MI paradigm without increasing the complexity of the task performed while significantly improved the decoding rate. In addition, compared to traditional enhancement methods such as electrical and somatosensory stimulations, closed-loop vibration stimulation has the advantages of simple equipment and comfortable wearing, which does not impose additional psychological burdens or excessive prep work on the subjects, and can effectively improve the overall performance of MI-BCI.

It has been shown that the tactile afferent input provided by vibration stimulation can increase the motor-related cortical excitability of subjects [51]. A similar phenomenon can be observed from Fig. 3 and Fig. 4. Combining the average ERD fluctuation from Fig. 8 and the peak ERD from Fig. 9, the left-hand MI task benefits more from the somatosensory stimuli. Regardless of whether the left or right hand was imagined, the vibratory stimuli generally enhanced the desynchronization of the C4 channel, and the ERD amplitude of the contralateral channel was significantly higher when the left hand was imagined than the right hand. Notably, the addition of the vibration stimulation resulted in enhancing ERD in the motor-sensory area contralateral to the imagined hand while also producing energy suppression on the ipsilateral side. That is a similar result observed in many studies that have applied tactile stimuli to both hands [23], [25], [27]. Although some studies have shown that ERD are often produced on the ipsilateral side with left hand MI [26], this desynchronization observed from the ipsilateral side of both tasks were certainly deriving from the activation of vibration stimuli. This phenomenon causes a reduction in the specificity of the ERD pattern in the left and right hand MI paradigm. At the same time, this phenomenon is also reflected in synchronization, as the p-values of the PLV in Table. I reflect that the CS produces almost no difference in PLV between the left and right hand tasks in the same frequency band and brain region. That is one of the reasons that in many studies the simultaneous application of vibration

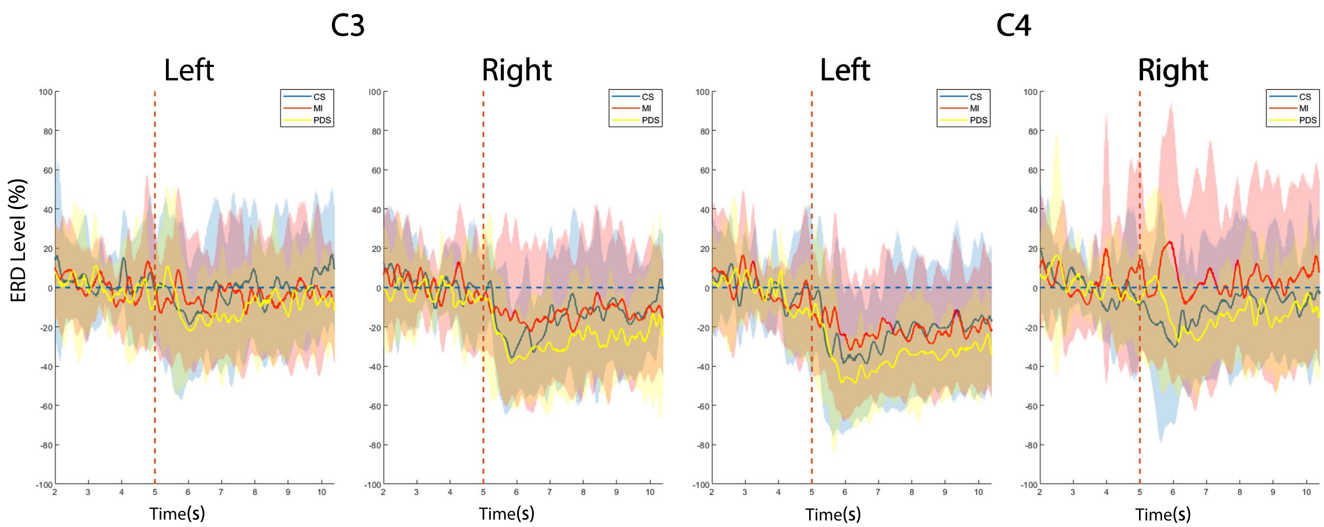

Fig. 8. The average ERD fluctuation graph of all subjects and trials in the alpha band. The blue, red and yellow curves correspond to the CS, MI and PDS tasks, respectively. The shading of the corresponding color represents the standard deviation of the corresponding task. The red dotted line represents the beginning of the imagery.

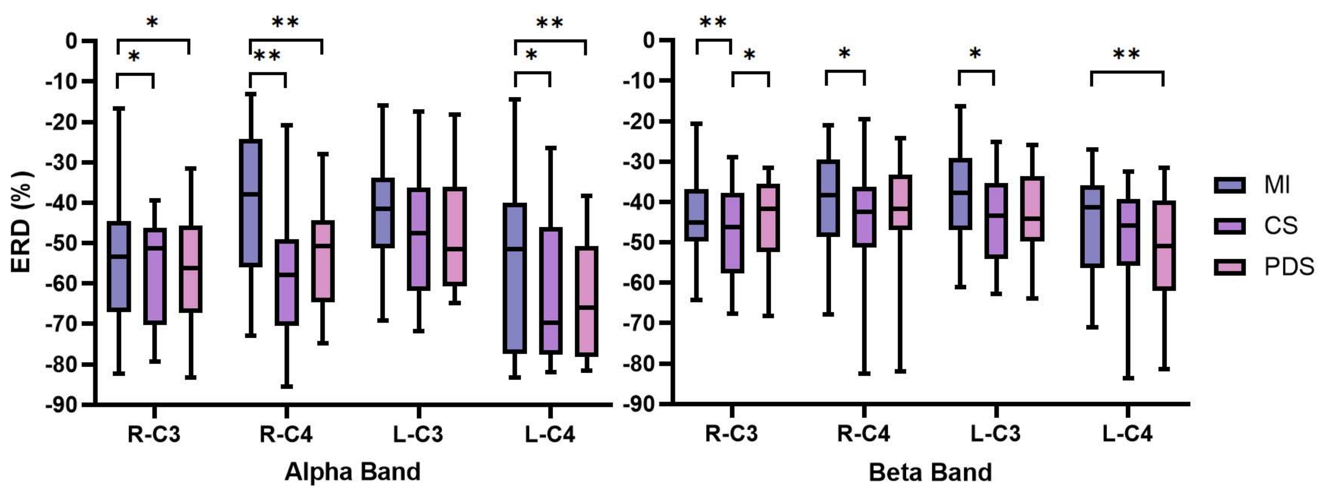

Fig. 9. The peak ERD values over the C3 and C4 electrodes for different sessions for all subjects.

stimuli in both hands was not effective in increasing MI decoding rates.

In the non-dominant hand study, continuous vibration stimulation also produced significant ERD within the rest task, whereas the effect of closed-loop vibration stimulation can be neglected. Although vibration feedback significantly increased motor cortical excitability, vibration stimulation alone does not induce significant ERD in the sensorimotor cortex. It needs to be combined with MI or selective sensation to produce an activation pattern. Nevertheless, it is difficult for subjects to not paying attention to unilateral vibratory stimuli in a rest task, whereas bilateral vibration stimuli in a two-handed task can somewhat affect their attention to either side of the imagery. In this study, many subjects reported that the rhythmic vibration stimuli provided by the closed-loop stimulus pattern helped them focus on the imagined hand, while the non-imagined hand was less affected. This is reflected in Fig. 8, where the PDS task produced persistent deepest ERDs in the sensorimotor area contralateral to the imagined hand, these ERDs is significantly stronger than the ones produced by CS task. In contrast, the ERD waveforms on the ipsilateral side of the imagined hand were not significantly different from the CS task.

Because MI shares some resources with the neural response network of tactile perception, sustained vibratory stimulation generates competition for resources. In turn, MI affects the perception of vibration stimuli, and it has been shown that MI significantly inhibits the phase synchronization of the ipsilateral SSSEP. It is found in Fig. 5 that, although the CS obtained the highest PLV means in the beta band of C3 local, it did not differ significantly from the MI due to the large disparity in response to beta frequency stimuli across subjects. Compared to both the MI and CS tasks, PDS task significantly improved the general enhancement of MI. Therefore, the MI and vibration stimuli are complementary, with closed-loop vibration stimuli reducing the negative effects of the MI task, such as sensory fatigue produced by prolonged single vibration stimuli. And the stimuli also retained and even enhanced the stimulation of cortical activity due to the precision of its application. In post-experiment interviews, several subjects reported being more attuned to the vibration rhythm of the closed-loop stimulation and were more able to focus on the imagination of movements. This may relate the closed-loop stimuli subjectively more with the somatosensory kinesthetic illusion and thus close the motor-sensory loop. Closed-loop stimuli are more effective in increasing neural correlation due to the fact that it increased the MI efficiency rather than increasing the vibration.

V. Limitations and Future Works

This paper explores the effect of phase-dependent closed-loop vibration stimulation on the overall performance of the MI task, while uses the phase features of the C4 channel as the stimulus trigger. There are still some limitations to this method of monitoring the real-time state of the brain because applying vibration stimulation and different imagery tasks can lead to dynamic oscillations in multiple brain regions. Using a multi-channel montage network to predict the oscillatory phase of the current target brain region is a feasible method to improve the accuracy of phase prediction. Furthermore, besides the phase characteristics, the amplitude of the oscillations may also affect the application of vibrational stimulus. The combination of phase and energy features may enable closed-loop vibration stimulation to further enhance the overall performance of MI-BCI and reduce the negative effects on concentration and perception.

Vibration stimulation has the advantages of high safety, high portability, no occupation of visual channels, and high acceptability. Previous studies have applied vibration stimulation to the rehabilitation training of stroke patients and other medical fields [52], [53]. The application of MI in stroke rehabilitation has been proven to positively affect the condition sickness. The closed-loop vibration stimulation proposed in this study can be used not only to enhance the MI performance in active rehabilitation training but also increase the motor-sensory-related cortical excitability in long-term training. Therefore helping patients speed up the process of neural reorganization, improve the efficiency of rehabilitation training, and assist in fine motor rehabilitation. We will investigate the long/short-term gain effect of closed-loop vibration stimulation applied on stroke patients, and explore its application in rehabilitation training in future works.

VI. Conclusion

This study investigated the effects of bilaterally applying the open- and closed-loop vibration stimulation on the overall performance of left and right hand motor imagery paradigms. Electrophysiological signal analysis showed that vibration stimulation could effectively enhance the activation of the sensorimotor cortex and the dynamic functional connectivity of the sensorimotor cortex during motor imagery. Comparing with the continuous vibration stimulation, the closed-loop vibration stimulation reduced interference with imagery tasks while promoting deeper and more sustained activation in the bilateral sensorimotor cortex. It can more efficiently combine sensory input with motor imagery and enable closed-loop vibration stimulation to significantly improve the classification accuracy of MI-BCI. With simple equipment, less preparatory work, and high user acceptance, the phase-dependent closed-loop vibration system can be applied to assist stroke rehabilitation training or benefit people with complete somatosensory systems but impaired motor functions.

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