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5 Hz rTMS improves motor-imagery based BCI classification performance *

Tianyu Jia, Linhong Mo, Chong Li, Aixian Liu, Zhibin Li, and Linhong Ji

***Abstract*— Brain-computer interface (BCI) based rehabilitation has been proven a promising method facilitating motor recovery. Recognizing motor intention is crucial for realizing BCI rehabilitation training. Event-related desynchronization (ERD) is a kind of electroencephalogram (EEG) inherent characteristics associated with motor intention. However, due to brain deficits poststroke, some patients are not able to generate ERD, which discourages them to be involved in BCI rehabilitation training. To boost ERD during motor imagery (MI), this paper investigates the effects of high-frequency repetitive transcranial magnetic stimulation (rTMS) on BCI classification performance. Eleven subjects participated in this study. The experiment consisted of two conditions: rTMS + MI versus sham rTMS + MI, which were arranged on different days. MI tests with 64-channel EEG recording were arranged immediately before and after rTMS and sham rTMS. Time-frequency analysis were utilized to measure ERD changes. Common spatial pattern was used to extract features and linear discriminant analysis was used to calculate offline classification accuracies. Paired-sample t-test and Wilcoxon signed rank tests with post-hoc analysis were used to compare performance before and after stimulation. Statistically stronger ERD (-13.93±12.99%) was found after real rTMS compared with ERD (-5.71±21.25%) before real rTMS ($p<0.05$). Classification accuracy after real rTMS (70.71±10.32%) tended to be higher than that before real rTMS (66.50±8.48%) ($p<0.1$). However, no statistical differences were found after sham stimulation. This research provides an effective method in improving BCI performance by utilizing neural modulation.**

***Clinical Relevance*— This study offers a promising treatment for patients who cannot be recruited in BCI rehabilitation training due to poor BCI classification performance.**

I. INTRODUCTION

Stroke has rapidly become the leading cause of severe motor disabilities which brought about a great need for effective rehabilitation therapies. The potential for motor recovery can be increased by reestablishment of functional sensorimotor loop [1].

The advantage of brain-computer interface (BCI) rehabilitation training lies in its mechanism to close the sensorimotor loop between motor intention and actual movement [2]. In BCI practice, recognizing motor intention is crucial for the efficiency of BCI training. However, BCI illiteracy problem is a common phenomenon in almost all kinds of BCIs [3], even for healthy practitioners. Considering moderate to severe brain deficits of stroke patients, motor-related cortical activities may be decreased or even hindered [4], which causes difficulties in detecting motor intention. Research has shown that event-related desynchronization (ERD) is a kind of electroencephalogram (EEG) inherent power characteristics associated with motor intention and often used to evaluate cortical activity [5, 6]. ERD can be easily detected during motor imagery (MI) and without need of actual movements [7], which is suitable for disabled patients. Enhancement of ERD contributes greatly to motor intention detection during BCI practice [8].

Non-invasive brain stimulation (NIBS) has been explored with great achievements in motor recovery, especially in cortical activity modulation, such as transcranial direct current stimulation (tDCS) and repetitive transcranial magnetic stimulation (rTMS) [9]. NIBS combined with BCI-based robotic therapy may greatly enhances the effectiveness of both treatments [10]. Ang et al. conducted tDCS before MI-BCI and results showed that averaged classification accuracy of using tDCS was higher than that of sham-tDCS [11]. rTMS has also been applied in motor recovery combined with BCI by suppressing the contralesional hemisphere, and results showed that increased relative ipsilesional cortical activation and significant alterations in inter-hemispheric inhibition was found in rTMS+BCI [12]. Besides suppressing the inhibition from the contralesional hemisphere, activating hemisphere with high-frequency rTMS has also been applied in clinical practice [13, 14]. Our study aims to explore the feasibility of boosting ERD by using rTMS, versus sham rTMS, and therefore improve MI-based BCI classification performance. To the best of authors' knowledge, there is still lack of research concerning improving BCI performance by applying high-frequency rTMS.

II. MATERIALS AND METHODS

A. Subjects

Eleven healthy subjects (age: 40.8±14.9, 5 female) participated in the experiments. All the subjects were right-handed without record of any neurological disorders and had no prior experience with BCI and MI before participating in the experiments. All subjects were informed of the experiment procedures before giving their written consent. The Ethical Committee of Beijing Rehabilitation Hospital of

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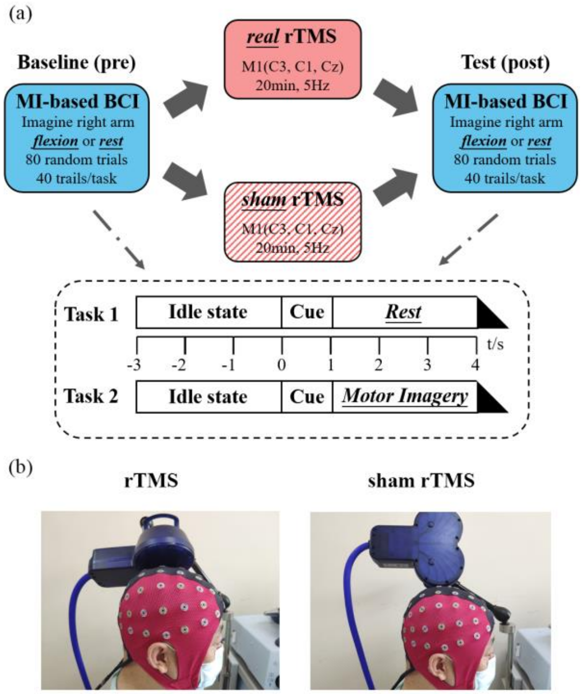

Figure 1. Experiment setup. (a) Time course of the experimental paradigm. (b) rTMS and sham rTMS.

Capital Medical University approved all experimental procedures involving human subjects.

B. *Experiment Description*

As shown in Fig.1(a), the experiment consisted of two conditions: rTMS + MI and sham rTMS + MI, which were arranged on different days. As shown in Fig.1(b), rTMS was conducted using a Magstim stimulator (Magstim Company, Spring Gardens, UK) with a figure-of-eight coil. Stimulation locations of the contralateral motor areas were determined via EEG electrode cap. During the rTMS phase, the coil was placed on the area mainly consisting of channels C1, C3 and Cz (three blue-shade channels in Fig. 2); sham rTMS was conducted with the plane of the coil tilted 90° [15]. rTMS was applied for 20 min at a rate of 5 Hz and using an intensity of 80% resting motor threshold (rMT). Motor imagery were arranged immediately before and after rTMS and sham rTMS. Thus, there were a total of 4 MI tests for each subject. During the MI tests, the monitor was placed approximately 1 m in front of the subjects. The MI test was divided into two tasks, consisting of 40 trials per task: rest and motor imagery. The two tasks were presented in a random order with 3-5 s random interval between each trial. Each trial started with a cross presented in the center of the monitor to instruct subjects to keep in idle state. After 3 s, a red upward arrow appeared to remind the subjects to imagine the right arm flexion until the cross disappeared from the monitor. If there was no arrow, subjects should just keep in resting state.

C. *EEG Recoding and Preprocessing*

During MI tests, EEG data were acquired using ANT eego^{TM} amplifier with 64 Ag/AgCl electrodes placed according to the international 10/20 system. Sampling rate was set as 500 Hz and electrode impendences were kept below 5 kΩ.The experiment paradigm was designed with OpenViBE 2.0.1. EEG data were referenced to the common average reference with exclusion of the 32nd channel EOG and then band-pass filtered using finite impulse response (FIR) from 0.5 to 40 Hz. Baseline corrections were performed before the artifacts were removed by an expert practitioner using independent component analysis (ICA).

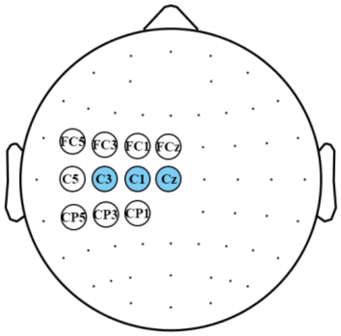

Figure 2. The electrodes used to measure ERD analysis and classification performance.

D. *Time-frequency Analysis*

After the preprocessing, EEG data were divided into 40 Task 1 trials and 40 Task 2 trials based on the trial marks. rTMS coil was placed over C3, C1 and Cz. Thus, the data from these three channels were analyzed to evaluate ERD changes. Time-frequency analysis of each trial was conducted using Morlet Wavelet in lower-alpha (alpha-, 8–10 Hz) and upper-alpha (alpha+, 10–13 Hz) range, respectively, with a step of 1 Hz. To maximize features and minimize noises, we computed the mean power spectral density (PSD) of low-alpha and up-alpha band respectively from the MI tasks with the following equation:

$$PSD_{b,c}(f,t)=\frac{1}{m}\sum_{tr=1}^{m}P_{b,c}(f,t) \qquad (1)$$

where b indicates alpha- or alpha+ band, c is a specific channel, f is a specific frequency band, t is a specific time interval, m is the total number of trials of motor imagery task, tr is a specific trial, and P is the PSD of a specific trial.

To analyze the ERD amplitude changes with respect to time, the ERD of the motor imagery state with respect to the idle state was computed with the following equation:

$$\mathrm{ERD}_{b,c}(t)=\frac{PSD_{b,c}(t)\text{-}PSD_{b,c,ID}}{PSD_{b,c,ID}}\times 100\% \qquad (2)$$

where $PSD_{b,c}(t)$ indicates the mean PSD over specific frequency band of motor imagery state, and $PSD_{b,c,ID}$ indicates the mean PSD over specific frequency band and specific time interval of idle state.

To analyze the overall motor imagery performance, the ERD ratio of each channel was computed with the following equation:

$$\mathrm{ERDratio}_{b,c}=\frac{PSD_{b,c,MI}-PSD_{b,c,ID}}{PSD_{b,c,ID}}\times 100\% \qquad (3)$$

where $PSD_{b,c,MI}$ indicates the mean PSD over specific frequency band and time of motor imagery state.

Several researches have proven that the most reactive frequency band may vary individually [6]. Thus, for each subject in the specific condition of experiment (rTMS or sham rTMS), the specific frequency band (*b*) for the above three equations was set by choosing the frequency band (alpha- or alpha+) that resulted in the maximum ERD ratio of motor imagery tasks pre and post rTMS or sham rTMS for each subject. To statistically depict the enhancement of cortical activation, paired-sample t-test with post-hoc analysis was used to compare overall motor imagery performance before and after rTMS/ sham rTMS respectively.

E. Feature Extraction and Classification Algorithm

The single-trial decoding accuracy between the task and idle states was used to evaluate offline MI-BCI performance. Common spatial pattern (CSP) was used to extract features from the preprocessed data filtered within 8-13 Hz. EEG data from the channels of stimulated-side sensorimotor cortex (signed with channel names in Fig. 2) were used as algorithm inputs. Linear discriminant analysis (LDA) was used to design classification models. 5-fold cross-validation was conducted 5 times generating classification accuracies. Then, the classification performance of each subject was evaluated with the average classification performance and standard deviation. Due to the non-normality of the data, Wilcoxon signed rank tests with post-hoc analysis was used to compare overall classification performance before and after rTMS/sham rTMS respectively.

III. RESULTS

A. Improvement of ERD Performance

The grand average ERD amplitude changes over time for two experiment conditions were compared in Fig. 3. Fig. 3(a) shows that there were greater ERD amplitudes from motor imagery post-rTMS compared to pre-rTMS. Apparent differences in the two ERD amplitudes were found in time domain. However, Fig. 3(b) shows that no apparent difference was found in ERD amplitudes with respect to time between post- sham rTMS and pre-sham rTMS.

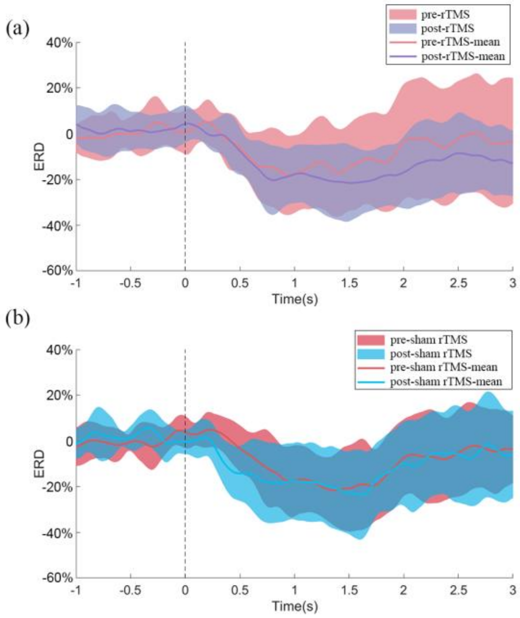

Figure 3. The grand average ERD amplitude changes over time of all subjects. The shaded region indicates standard deviation of ERD amplitude changes. Comparison of ERD amplitude (a) between pre-rTMS and post-rTMS, and (b) between pre-sham rTMS and post-sham rTMS.

Comparison of ERD ratio between pre-rTMS and post-rTMS was conducted by using paired-sample t-test with post-hoc correction. Results showed that ERD ratio from post-rTMS (-13.93±12.99%) was statistically significant compared to that from pre-rTMS (-5.71±21.25%) ($p<0.05$). However, no statistical differences were found in ERD ratio before and after sham rTMS ($p=0.61$).

B. Enhancement of MI-BCI Performance

Fig. 4 presents comparisons of offline classification accuracy with 5-fold cross-validation in different experimental conditions. Fig. 4(a) shows that all subjects achieved better classification performance in MI post-rTMS compared to pre-rTMS, except for S6 and S9. Classification accuracy after real rTMS (70.71±10.32%) tended to be higher than that before real rTMS (66.50±8.48%) ($p<0.1$) However, as shown in Fig. 4(b), no statistical differences were found in accuracy before and after sham rTMS ($p= 0.86$).

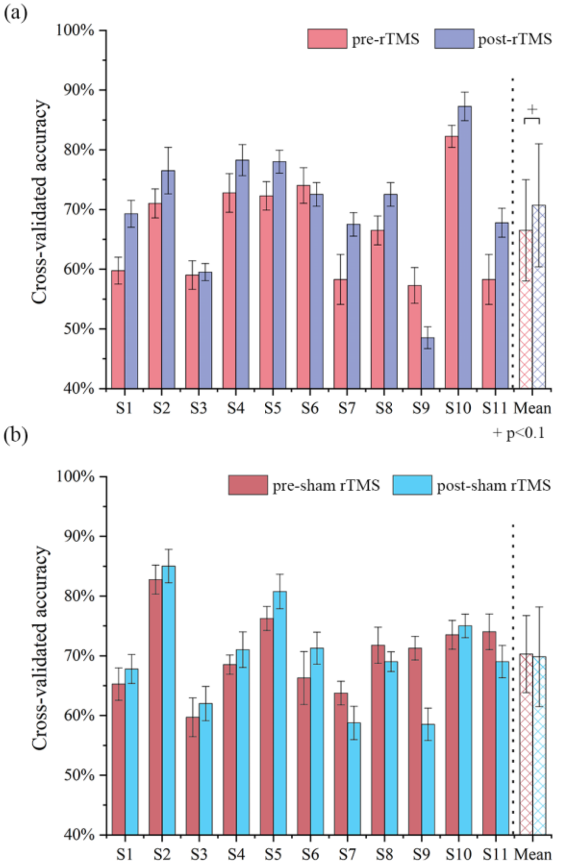

Figure 4. Comparison of offline classification accuracy (a) between pre-rTMS and post-rTMS, and (b) between pre-sham rTMS and post-sham rTMS. Error bars for each subject indicate standard deviation and for mean values indicate standard error of mean. +indicates p<0.1.

IV. DISCUSSION

In our study, two conditions of the experiment, using rTMS and sham rTMS, were held to investigate the effect of a specific neural modulation technology on motor imagery practice. By comparing the ERD amplitude and MI-BCI classification performance, evidence has been provided that high-frequency rTMS modulation can result in enhancement of motor imagery performance.

It has been previously proven that TMS modulation made positive effect on cortical and corticospinal activation both in healthy [16, 17] and stroke patients [18]. rTMS triggered by μ-rhythm has been proven to lead to long-term potentiation in corticospinal activation for healthy people [16]. Previous research also found relative ipsilesional cortical activation from fMRI after TMS modulation in stroke patients [12]. The results of this research provide more evidence to this conclusion. More importantly, our study further proved that it enhanced the motor-related cortical activities during MI practice. In our study, greater ERD features were found for five subjects after rTMS who had no apparent ERD during MI practice before rTMS modulations. Besides, several other forms of input stimulation have been also proven efficient in boosting ERD during BCI training, such as tactile stimulation [8] and immersive visual input stimulus [6]. It may inspire us that multisensory stimulus input could enhance cortical activation and naturally improve BCI performance. It is notable that apparent differences were found nearly at the beginning of MI practice in the ERD amplitude changes with respect to time as shown in Fig. 3(a). Besides, ERD amplitude increase was also found during cue period. ERD increase during cue period may result from preparation of instructed MI tasks. It shows that rTMS modulation can improve the performance of actual MI practice but whether it can influence the movement preparation patterns should be validated further in large populations.

Research has shown that a part of subjects who are not proficient with BCI systems are called "BCI illiteracy" [19]. Much efforts have been made in solving the problem. Vidaurre et al. proposed a novel adaptation scheme in BCI practice, and results showed that better control over BCI system was obtained accompanied with sensory motor rhythm changes for BCI illiterates [3]. One of the most important factors for BCI illiteracy users is that they cannot generate detectable brain activity during BCI practice which can be characterized by no MI-related fMRI activity and ERD [20]. Accordingly, we can infer the possible solution to this problem is to enhance cortical activation and therefore be able to produce detectable electrophysiological features. On the whole view, for rTMS experiment, improvement of classification performance was found accompanied by a marked enhancement of ERD amplitude. However, not all of the subjects reacted positively to the intervention, consisting of S6, S9 and S10. Apparent ERD was still not found after rTMS intervention for S9. Classification performance depends on the differences between the task state and the idle state. Electrophysiological features' changes of task states do not linearly correlate with the improvement of classification performance. In further studies, it may be worthwhile to explore electrophysiological features' changes of idle states with rTMS modulation, which also influences the classification performance to some extent.

Several limitations exist in the present study. This is a pilot study to explore the feasibility of boosting ERD and improving BCI classification performance by using high-frequency rTMS in healthy people. With the aim of applying this method in clinical practice, further validations should be conducted in stroke patients. Besides, for stroke patients, the cortical reorganization is individualized and the activation patterns are varied, such as contralesional compensations [21]. In the further validation, the personal activation pattern should be recognized first and rTMS can be applied on the interested brain area.

V. CONCLUSION

This research provides an effective method in improving BCI performance by utilizing neural modulation. It demonstrated, with rTMS modulation, a statistically significant improvement of ERD amplitude was found and classification accuracy after real rTMS tended to be higher. This study offers a promising treatment for patients who cannot be recruited in BCI rehabilitation training due to poor BCI classification performance.

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