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Motor imagery BCI for upper limb stroke rehabilitation: an evaluation of the EEG recordings using coherence analysis

Sau Wai Tung[1], Cuntai Guan[1], Kai Keng Ang[1], Kok Soon Phua[1],
Chuanchu Wang[1], Ling Zhao[2], Wei Peng Teo[2] and Effie Chew[2]

Abstract— **Brain-computer interface (BCI) technology has the potential as a post-stroke rehabilitation tool, and the efficacy of the technology is most often demonstrated through output peripherals such as robots, orthosis and computers. In this study, the EEG signals recorded during the course of upper limb stroke rehabilitaion using motor imagery BCI were analyzed to better understand the effect of BCI therapy for post-stroke rehabilitation. The stroke patients recruited underwent 10 sessions of 1-hour BCI with robotic feedback for 2 weeks, 5 times a week. The analysis was performed by computing the coherences of the EEG in the lesion and contralesion side of the hemisphere from each session, and the coherence index of the lesion hemisphere ($0 \leq CI \leq 1$) was computed. The coherence index represents the rate of activation of the lesion hemisphere, and the correlation with the Fugl-Meyer assessment (FMA) before and after the BCI therapy was investigated. Significant improvement in the FMA scores was reported for five of the six patients ($p = 0.01$). The analysis showed that the number of sessions with $CI \geq 0.5$ correlated with the change in the FMA scores. This suggests that post-stroke motor recovery best results from the activation in the lesion hemisphere, which is in agreement with previous studies performed using multimodal imaging technologies.**

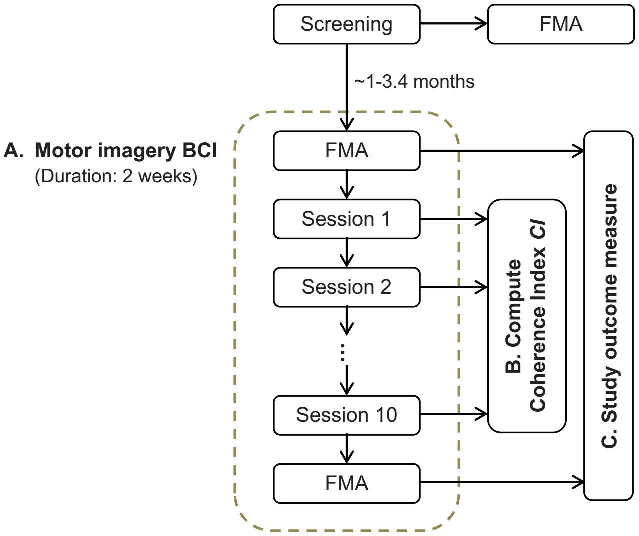

Fig. 1. Flowchart of the study of EEG recorded during motor imagery BCI, together with the benchmark study outcome measure.

I. INTRODUCTION

Brain-computer interface (BCI) technology has been developed as an alternative modality for post-stroke rehabilitation, where stroke patients are able to interact with the environment through their brain signals rather than through muscles [1]. Some recent advances in this area include using BCI to modulate specific brain frequency rhythm [2], using multimodal electric and magnetic brain activity BCI to drive an orthosis [3], and using BCI to trigger functional electrical stimulation for movement practice [4].

Despite much interest in this alternative post-stroke rehabilitation modality, the successes of BCI-based methodologies have most often been limited to output peripherals such as robots, orthosis and computers [1]. These peripherals function as black-boxes where no direct explanation can be provided for the efficacy of the BCI technology on post-stroke rehabilitation. Subsequently, a better understanding of BCI related neuroplasticity depends very much on multimodal imaging approaches such as functional magnetic resonance imaging, diffusion tensor imaging, magnetoencephalography and transcranial magnetic stimulation [5]. These imaging technologies can be costly and cumbersome to operate.

In this paper, we directly employ the EEG signals recorded during the course of BCI-based rehabilitation for stroke patients to track the effect of the BCI technology on brain plasticity. In particular, the EEG signals recorded during a motor imagery BCI for upper limb stroke rehabilitation is investigated. This is because motor imagery, which involves the mental rehearsal of a physical movement, provides a means to access the motor system for rehabilitation at all stages of stroke recovery [6]. In addition, the ability of patients to perform motor imagery is shown to be intact even after the onset of stroke [7][8][9]. Since coherence allows detection of activities in electrode pairs at frequencies that are phase-consistent over many trials [10], EEG coherence analysis is used to determine activations in the brain during the BCI therapy. Results achieved agrees with previous studies using multimodal imaging technologies [11][12], i.e., post-stroke motor recovery best comes from the activation in the lesion hemisphere.

II. METHODS

This section describes the clinical study, with approval from the Ethics Approval Board, conducted on hemiparetic

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[1] S. W. Tung, C. Guan, K. K. Ang, K. S. Phua, and C. Wang are with Institute for Infocomm Research, Agency for Science, Technology and Research (A*STAR), 1 Fusionopolis Way, #21-01, Connexis, Singapore 138632. (Email: {tungsw, ctguan, kkang, ksphua, ccwang}@i2r.a-star.edu.sg).

[2] L. Zhao, W. P. Teo and E. Chew are with National University Hospital, 5 Lower Kent Ridge Road, Singapore 119074. (Email: {ling_zhao, wei_peng_teo, Effie_CHEW}@nuhs.edu.sg).

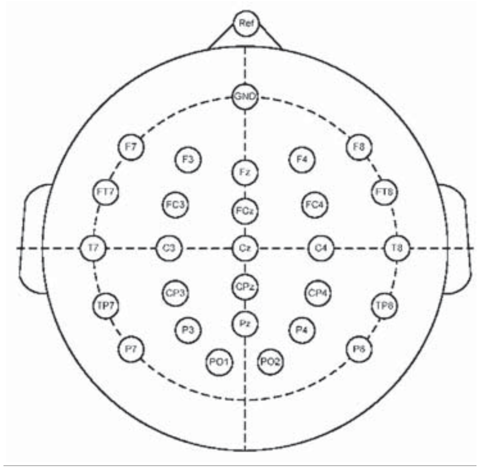

Fig. 2. Positions of the 27 EEG channel locations.

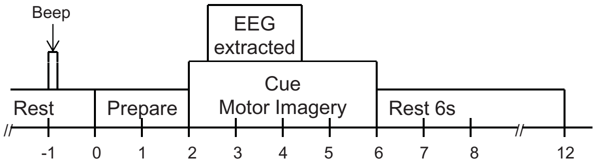

Fig. 3. Timing of the motor imagery BCI.

Fig. 4. Setup of EEG-based motor imagery BCI with robotic feedback rehabilitation for stroke.

stroke patients using EEG-based motor imagery BCI with robotic feedback rehabilitation. The calculation of the coherence index is then presented. Finally, a study outcome measure using the Fugl-Meyer assessment (FMA) for motor recovery after stroke is described. Fig. 1 shows a flowchart of this study.

A. Motor imagery BCI

Six BCI naive hemiparetic stroke patients were recruited in this study. They underwent a screening session, between 1 month to 3.4 months prior to the BCI therapy, to evaluate that they can operate a EEG-based motor imagery BCI [13]. 27 channels of EEG data were collected from each subject using Nuamps acquisition hardware (http://www.neuroscan.com) with unipolar Ag/AgCl electrodes sampled at 250 Hz. Fig. 2 shows the positions of the EEG channel locations, with the reference electrode located on the naison. The stroke affected limb of a subject was strapped to the MIT-Manus robot. The subjects underwent 10 sessions of 1-hour BCI therapy for 2 weeks, 5 times a week. A total of 160 trials of EEG per session, comprising of motor imagery of the stroke affected upper limb, were collected. Each trial lasted approximately 12 s. For each trial, the subject was first prepared with a visual cue for 2 s on the screen, and another visual cue then instructed the subject to perform motor imagery, followed by a 6 s rest. Fig. 3 shows the timing for the trial. 10 minutes of rest were given in between every 40 trials. If motor imagery was detected, a movement feedback was provided by the MIT-Manus robot in moving the stroke affected limb towards the goal display on screen, and back to the origin of the clock game interface [13]. Fig. 4 shows the setup for the motor imagery BCI with robotic feedback. The EEG signals of the motor imagery were extracted 0.5 to 2.5 s after the visual cue was shown to the subject.

B. Coherence index (CI)

The coherences of the EEG recordings in the lesion and contralesion side of the hemisphere were computed for each session. Although 27 channels were captured in the recordings, only 15 channels were considered, i.e., FT7, T7, TP7, FC3, C3, CP3, FCz, Cz, CPz, FC4, C4, CP4, FT8, T8, and TP8. These channels correspond to the motor region of the brain. To differentiate between the lesion and contralesion hemisphere, two channels (C3 and C4) were considered. In each trial, coherence connections C, taken over an average across the frequencies $F = 4 - 45$ Hz, were computed for 8 different channels on the two hemispheres respectively as shown in (1):

$$C_{XY}(F) = \frac{|P_{XY}(F)|^2}{P_{XX}(F)P_{YY}(F)} \tag{1}$$

where

$$P = \text{power spectral density}$$
$$\begin{cases} X = \text{C3}, \\ Y = \text{FCz, Cz, CPz, FC3, CP3, FT7, T7, TP7} \end{cases} .$$
$$\begin{cases} X = \text{C4}, \\ Y = \text{FCz, Cz, CPz, FC4, CP4, FT8, T8, TP8} \end{cases}$$

Comparisons between the 8 corresponding connections in the two hemispheres were performed over the 160 trials. Subsequently, the activated connection of a particular comparison was chosen as that with the most number of winning trials. For example, the activated connection is chosen to be that between C3 and FC3 if the number of trials for which the connection C3–FC3 is activated is more than that for the connection C4–FC4. The coherence index $0 \leq CI \leq 1$ for the lesion hemisphere was then calculated as the average number of activated connections in the hemisphere. Thus, the lesion hemisphere was regarded as the more activated one when $CI \geq 0.5$.

C. Study outcome measure

Before the start of the BCI therapy, the subjects were required to complete the Fugl-Meyer assessment (FMA) to

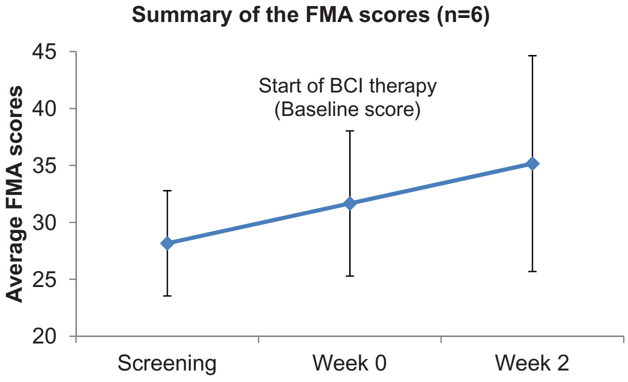

Fig. 5. Summary of the average (standard deviation) FMA scores.

assess their motor impairment. The FMA consists of a 66-points scale such that a greater impairment is associated with a lower score. The FMA was completed again at the end of 2 weeks, and the outcome measure of the BCI therapy was the change in the FMA scores between weeks 0 (baseline) and 2. In addition, the FMA assessment was also performed during the screening session.

III. RESULTS AND DISCUSSIONS

Fig. 5 shows a summary of the average FMA scores during the screening session, and at weeks 0 and 2. There was an average improvement of 3.5 in the FMA scores between the screening session to week 0, from 28.2 (± 4.62) to 31.7 (± 6.38). All the subjects showed either positive or no improvement during this period. A paired t-test between week 0 and screening indicated no significant improvement within the group. Next, we observed that there was again an average improvement of 3.5 in the FMA scores for the group between week 0 to week 2, from 31.7 (± 6.38) to 35.2 (± 9.47). However, positive improvements in scores were observed in only five out of the six subjects. Changes of the five positive outcome measures at week 2 from baseline were then assessed by a paired t-test, and the resultant improvement was statistically significant ($p = 0.01$). This suggests that aside from the natural recovery of the subjects, the 2 weeks BCI therapy is generally effective for post-stroke rehabilitation. Nevertheless, it is unclear from Fig. 5 the effect of the BCI therapy on the individual subjects, i.e., accountability of the varying degrees of improvement for different subjects.

Correlation analysis was next performed between the change in FMA scores and the average rate of activation of the lesion hemisphere between week 2 and baseline as shown in Fig. 6. There was a strong positive correlation between the change in FMA scores and the number of sessions with $CI \geq 0.5$, i.e., a Pearson's correlation coefficient of 0.819, which is statistically significant with $p = 0.046$. This indicates that improvement in motor recovery was associated generally with increasing activation in the lesion hemisphere during the BCI therapy, and the result is in line with observations made in previous multimodal imaging studies [11][12].

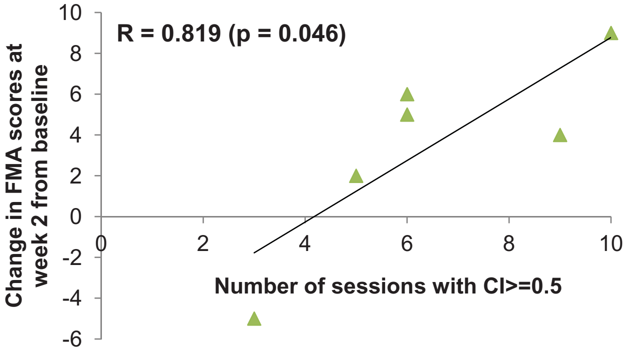

Fig. 6. Correlation between the change in FMA scores and the average rate of activation of the lesion hemisphere (given as the number of sessions with $CI \geq 0.5$) from week 0 to week 2.

IV. CONCLUSIONS

This paper presented the analytic results of the EEG recorded during the course of upper limb stroke rehabilitation using motor imagery BCI, whereby the EEG was used to track the effect of the BCI-based therapy on brain plasticity. Since the efficacy of BCI technologies have most often been demonstrated through output devices such as computers and robots which are black-boxes, a better understanding of BCI on brain plasticity depends greatly on multimodal approaches [1]. This study investigates if a direct application of the EEG signals can be used to track the performance of BCI-based stroke rehabilitation therapy.

The subjects recruited underwent 10 sessions of 1-hour BCI with robotic feedback for 2 weeks, 5 times a week. They also underwent a screening session to assess their ability to operate a EEG-based motor imagery BCI [13]. As a measure to tabulate their motor impairment, the subjects were required to complete the Fugl-Meyer assessment (FMA) during the screening session, prior to the BCI therapy, and after the BCI therapy. The coherence index CI, which represents the rate of activation of the lesion hemisphere, was computed for each session. The result of using the coherence index to track the changes in the FMA scores was presented.

All the subjects showed either no or positive improvement from natural recovery during the period from the screening session to the start of the BCI therapy. However, the average improvement was not statistically significant. After 2 weeks of BCI therapy, five of the six subjects showed statistically significant positive improvements in their FMA scores. To answer the question of why there were varying improvements seen in different subjects, a correlation analysis was performed between the change in FMA scores and the average rate of activation of the lesion hemisphere (as measured by the number of sessions with $CI \geq 0.5$) between weeks 0 and 2. A statistically significant positive correlation between the change in FMA scores and the number of sessions with $CI \geq 0.5$ was observed. This suggests that improvement in motor recovery most likely comes from increasing activation in the lesion hemisphere during BCI therapy, and the result agrees with existing multimodal studies [11][12].

The present result indicates that it is possible to track the effect of BCI technology on brain plasticity directly using EEG signals. Further analysis of the direct application of EEG is worthwhile to assess if there is any clinical predictor for the effect of BCI therapy as a post-stroke rehabilitation modality.

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