BCI-FES training system design and implementation for rehabilitation of stroke patients

Fei Meng, Kai-yu Tong, *Member, IEEE*, Suk-tak Chan, Wan-wa Wong, Ka-him Lui, Kwok-wing Tang
Xiaorong Gao, *Member, IEEE* and Shangkai Gao, *Fellow, IEEE*

***Abstract*—A BCI-FES training platform has been designed for rehabilitation on chronic stroke patients to train their upper limb motor functions. The conventional functional electrical stimulation (FES) was driven by users' intention through EEG signals to move their wrist and hand. Such active participation was expected to be important for motor rehabilitation according to motor relearning theory. The common spatial pattern (CSP) algorithm was applied as one pre-processing step in brain-computer interface (BCI) module to search for the optimal spatial projection direction after brain reorganization. The pre- and post- clinical assessment was conducted to identify the possible functional improvement after the training. Two chronic stroke subjects attended this pilot study and the error rate of the BCI control was less than 20% after training of 10 sessions. This implementation showed the feasibility for stroke patients to accomplish the BCI triggered FES rehabilitation training.**

I. INTRODUCTION

Functional electrical stimulation (FES) and motor imagery have been extensively applied in the rehabilitation training of stroke patients [1-4]. However, the passive FES was lack of the patients' intention to recover which has been thought to be the important factor of motor relearning theory [5]. The pure motion imagery had the problem of performance variability due to the absence of feedback indication. Brain-computer interface (BCI) has been proved to be a potential method to link the brain and the outward environment directly [6]. It showed the great perspective to help especially the "lock-in" people to regain or recover their ability to communicate and control [7]. The idea that FES therapy triggered by the active intention possibly help the stroke patients to recover by combining the agitation from the central nervous system (CNS), the corresponding muscle stimulation and the afferent sensory feedback. In current study, we integrated the motor imagery based BCI with FES to facilitate the motor recovery after stroke. The goal of this study was to show the feasibility of the training platform for the chronic stroke patients and to evaluate the effect of the therapeutic strategy.

One important issue in BCI system design was the optimal electrode(s) selection. Growing evidences showed that the brain experienced reorganization after accident like stroke. The displacement in primary motor cortex (M1) was observed in studies with functional magnetic resonance imaging (fMRI), PET and transcranial magnetic stimulation (TMS) [8-10]. This displacement possibly reflected the local network relocation to recover the lost motor function in M1. However the direction of the shift was with great variability which made it difficult to identify the optimal electrodes choice for BCI system implementation. Common spatial pattern (CSP) was proved to be one mature pre-processing method in BCI studies with multiple channels recording [11]. The spatial filter calculated by CSP could detect the optimal spatial projection orientation to maximize the differentiation of mental state between two tasks. Therefore we adopted CSP in current study to overcome the difficulty of brain reorganization for feature extraction.

II. METHOD

The criteria for subject recruitment included: 1) chronic stroke patients (more than 12 months from the onset); 2) unilateral cerebral infarction after a first-ever stroke event; 3) age from 20 to 70; 4) wrist extension and opening hand could be achieved with help of FES. The exclusion criteria included the uncontrolled medical problems, serious cognitive deficits which prevented the ability to give informed consent and perform the training tasks and participation of similar study at the same time.

The functional recovery of upper limb especially the wrist and hand was important for the stroke patients to execute the activities of daily living (ADL). Therefore the FES aimed for the repetitive stimulation of wrist and hand extensors in our study. The FES electrodes were put on the extensor carpi radialis (ECR) and opponens pollicis (OP) muscles to induce the simultaneous wrist extension and hand opening. The goniometer was utilized to monitor the change of wrist angle

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Fei Meng is with the Department of Biomedical Engineering, Tsinghua University, Beijing 100084, China and the Department of Health Technology and Informatics, Hong Kong Polytechnic University, Kowloon, Hong Kong, China.

Kai-yu Tong is with the Department of Health Technology and Informatics, Hong Kong Polytechnic University, Kowloon, Hong Kong, China.

Suk-tak Chan is with the Department of Health Technology and Informatics, Hong Kong Polytechnic University, Kowloon, Hong Kong, China.

Wan-wa Wong is with the Department of Health Technology and Informatics, Hong Kong Polytechnic University, Kowloon, Hong Kong, China.

Ka-him Lui is with the Department of Health Technology and Informatics, Hong Kong Polytechnic University, Kowloon, Hong Kong, China.

Kwok-wing Tang is with the Department of Diagnostic Radiology and Imaging, Queen Elizabeth Hospital, Hong Kong, China.

Xiaorong Gao is with the Department of Biomedical Engineering, Tsinghua University, Beijing 100084, China.

Shangkai Gao is with the Department of Biomedical Engineering, Tsinghua University, Beijing 100084, China.

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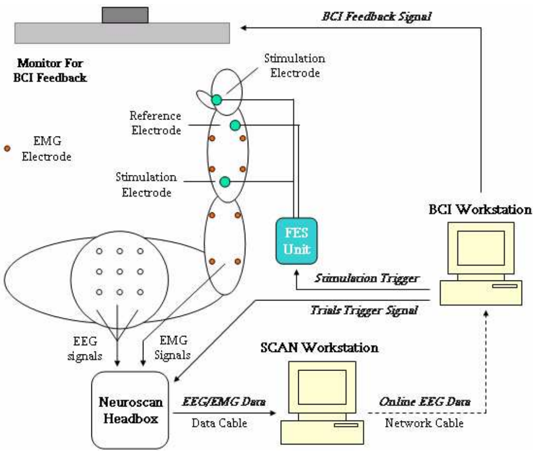

Fig. 1. The framework of the BCI-FES training system.

induced by FES across the whole session. The muscle fatigue could be detected as the decrease of the wrist angle during electrical stimulation and this has been avoided during the whole experiment.

The 64-channel EEG system (Neuroscan, Neuroscan Inc.) was adopted in current study. The linked electrode from left and right mastoid was used as the reference and the sample rate was set to 250 Hz. We also recorded the electromyographic activities from forearm and upper limb muscles to monitor the motion artifact. All the impedances were kept below 5K ohm. Electroencephalographic (EEG) signals from 18 electrodes around C3 and C4 according to the international 10-20 system were selected to construct the features vector using power in the mu band (8-15 Hz). Before calculating the feature vector, the multi-channel EEG signals were pre-processed with CSP algorithm to find the optimal spatial projection direction. The advantage of CSP pre-processing was to adapt to the possible shift of functional representation in M1. The power in the mu band was calculated on the spatial filtered EEG signal. The fisher discriminate analysis (FDA) was utilized to search for the hyperplane in the feature space and classify the features. The spatial filters and parameters of linear classifier were trained during the first six trials in 1st run. After that those parameters will be updated in an adaptive way by using the data from last six trials. This adaptation process was executed trial by trial to promote online accuracy of the motor imagery. The trials from last run were utilized at the beginning of the training from the 2nd run to improve performance of feedback control, e.g., the adaptation process at the end of 3rd trial of 4th run would formulate the training dataset with last three trials in 3rd run and first three trials in 4th run. The framework of the system design was showed in figure 1.

The subject was instructed to imagine the movement of their wrist and hand for example, like lifting up the hand repeatedly, to trigger the FES. The goal of the BCI module was to differentiate the brain state of motor imagery from being relax. We designed an unique "Immobilization" state in which the subject should avoid any kind of motion artifact. The subject could relax himself/herself in the rest of a trial. The BCI module used the EEG data from immobilization state to identify whether the subject was executing the motor imagery of wrist and hand.

The state transition of the BCI module was illustrated in figure 2. Each trial started with "Focus" cross with 3 seconds. After the cross disappeared, there was one blue block displayed in the same side with the hemiplegia as the target. The subject was instructed to imagine the motion of his/her affected wrist and hand after the feedback ball appeared in the bottom center of the screen. The feedback ball ran towards the top of the screen smoothly as time passed by and the BCI module adjusted the horizontal location of the feedback ball with one step according to the subject brain state in the last second every 0.2 second. The imagination was treated as success if the feedback ball hit the target block and the FES will be triggered. The initial length of the target was the half width of the screen. We adopted adjustable threshold according to the subject's performance to encourage the subject to achieve better control. Three successively successful hit would decrease the length of the target block by one to increase the difficulty of next trials. And two successively failures would increase the length of the target block by one. The minimum and maximum limit of the width

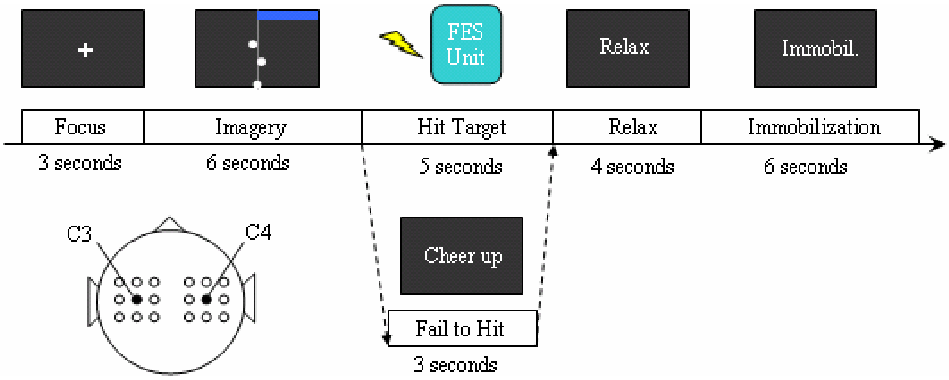

Fig. 2. The machine state transition of the each trial (Immobil. – immobilization)

of the target was the quarter and half of the screen length. The NetAcquire function of the Acuqire 4.3 (Neuroscan, Neuroscan Inc.) was used to transmit the recorded EEG data to the BCI control module in real-time.

Before the training two clinical assessments were conducted to evaluate the functional status of the subject. The content of assessment included upper extremity portions of Fugl-Meyer Assessment (FMA) [12], Modified Ashworth Scale (MAS) and Action Research Arm Test (ARAT) [13]. The whole BCI-FES training included 20 sessions and should be completed within two months. In each session the subject experienced four runs and each run contained 20 trials. The maximum number of successful FES induced movement was 80 in each training day. The intermittent break between two successive runs was at least two minutes to avoid mental fatigue. After finishing 20 sessions, one post-assessment and one three months follow-up assessment would be conducted to evaluate the effect of the whole BCI-FES training.

III. RESULT AND DISCUSSION

Two stoke patients participated our study and both of them could achieve error rate less than 30% after several sessions. The online error rate was further decreased to less than 20% after 10 sessions. Figure 3 showed one of our stroke patients in the training process. The event related desynchronization (ERD) and event related synchronization (ERS) changes of one subject averaged across trials in one session were shown in figure 4. The vertical blue dotted line in each sub-figure indicated the onset of the motor imagery. The red dotted line corresponded to the startup of the FES and the green dotted line meant the onset of the immobilization. The x-axis of each sub-figure was time in seconds and the y-axis was frequency in Hz. The relax period was easily contaminated with artifact; therefore it was removed from this analysis. This subject suffered from right side hemiplegia. ERD related to the motor imagery of affected upper limb was observed in the area around C3 and C4. However the ERD was greater on the ipsilateral sensorimotor area especially in the beta band, which was different from the observation of healthy subjects. This possibly resulted from the brain plasticity after stroke. Indeed recent studies on neural imaging and functional recovery after stoke proposed that the abnormal activation pattern in affected-side tasks possibly reflected the absence of inhibition from injured hemisphere to the intact hemisphere. As the EEG data across the whole training were recorded, we could identify that whether the functional improvement, if existed after the therapy, benefited from the increased inter-hemisphere inhibition from the affected sensorimotor cortex to the unaffected one. And such analysis could provide more evidences about the functional role of the regional interaction in the execution of movement under pathological conditions.

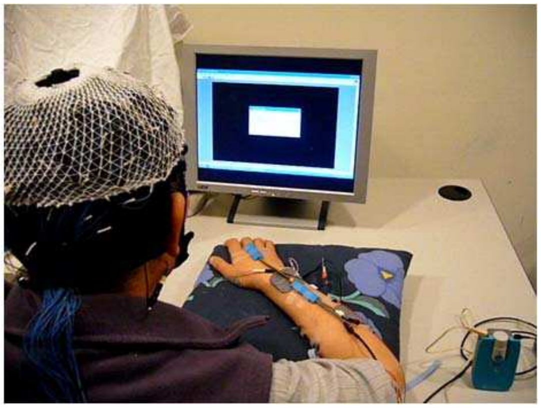

Fig. 3. The snapshot of the BCI-FES training with one of our stroke subjects

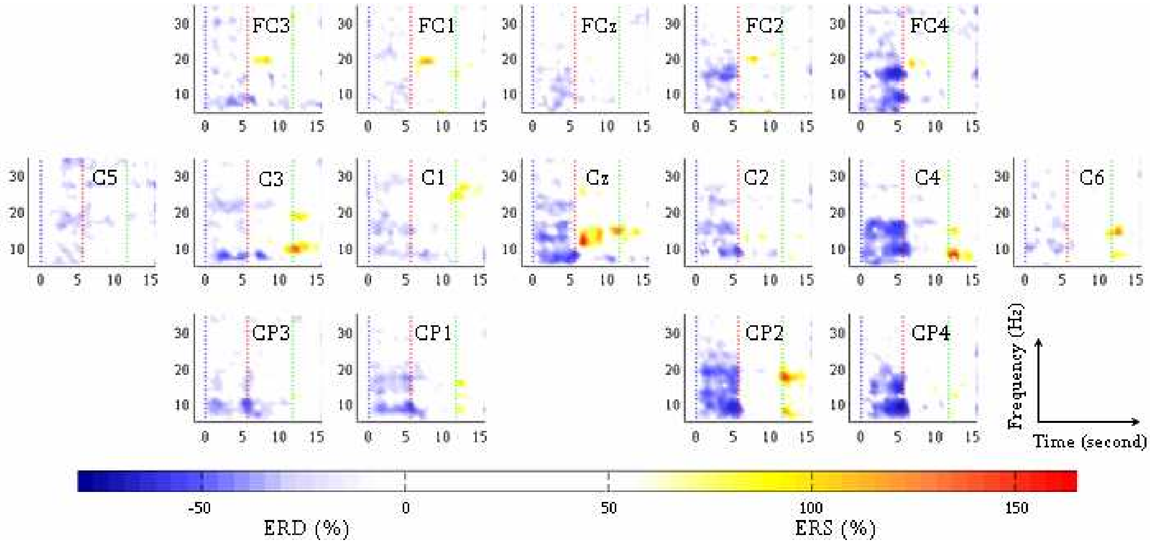

Fig. 4. The ERD/ERS topographic map of the BCI-FES training

This is an on-going project, more subjects are training in this project and more results will be reported after the completion of the project.

IV. CONCLUSION

The system design and implementation in this paper has been proved to be feasible for the rehabilitation training for chronic stroke patients. More subjects will be invited to evaluate the robustness and the training effect on functional recovery of the stroke patients.

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