EEG-controlled Table Bike for Neurorehabilitation Based on Sensorimotor-rhythm BCI

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***Abstract*—This work demonstrates an EEG-controlled table bike for neurorehabilitation based on the sensorimotor rhythm (SMR) BCI using a wearable ultra light-weighted 4-ch wireless EEG device designed and developed by our group. The 4-ch wireless EEG module was used to acquire high quality EEG signals from the scalp locations of C3 or C4 or both. The acquired EEG data were then processed and analyzed using an EEG translation module, also designed by our group, to extract the SMR features. Consequently, the SMR features were used to turn ON and OFF a commercially available table bike for neurorehabilitation process. Finally, the feasibility of the devised EEG-controlled table bike was tested on normal subjects using a motor imagery experiment, in which the subjects were asked to perform a motor imagery task every time a 'go' cue was displayed at the center of a computer screen and move the table bike without physical hand movement. In total, 12 healthy normal subjects and one chronic stroke patient participated in this study. The success rate at which the subjects/patient could successfully move the table bike after the cue onsets was used to evaluate the feasibility of the device. Our result showed that most of the subjects and patient could easily learn how to operate the EEG-controlled table bike with only few sessions of training (no more than 30 minutes) and achieve around 80% success rate.**

Keywords-neurorehabilitation; sensorimotor rhythm (SMR); brain-computer interface; EEG.

I. INTRODUCTION

In order to put the brain in the loop of neurorehabilitation process [1], this work devised a brain-computer interface (BCI)-based electroencephalography (EEG) controlled table bike for training patients after stroke attack and restoring their motor control potentially through reorganizing the otherwise missing or degenerated fiber tracts directly or indirectly caused by stroke. Recent development of BCI-based neurorehabilitation has proved beneficial in helping the patients to restore their motor control, which was damaged by stroke and/or other brain injury or degeneration [2, 3]. Among all the BCI-based neurorehabilitation mechanisms, motor imagery induced sensorimotor rhythm (SMR) is probably the most pronounced brain signature, which has been largely applied to interface with rehabilitation hardware or robots for neurorehabilitation process [1, 4]. Although such SMR feature is ubiquitous across different brain imaging modalities, such as functional magnetic resonance imaging (fMRI), electroencephalography (EEG), and megnetoencephalography (MEG), EEG is so far the most preferable modality for this purpose, due mainly to the cost and availability [4, 5].

However, the form factor of most currently available EEG devices is still too bulky for portable or even wearable requirement for neurorehabilitation process. In addition, the wires connecting the EEG electrodes and the signal acquisition computer could be an obstacle to the EEG-based neurorehabilitation device as they can accidently be caught by the moving arms of the device and thus disrupt the rehabilitation process. As a result, wireless transmission of digitized EEG data to the feature extraction module for looking for SMR patterns can be valuable to make the rehabilitation process smooth [6]. On the other hand, given that the source of SMR is known to be present in the sensorimotor and superior parietal cortices and can be extracted using scalp EEG with electrodes placed on the locations near C3 or C4 or both [7, 8]. Therefore, an EEG system with three to four channels should be more than enough for the SMR-based BCI neurorehabilitation application. It is thus possible to devise a light-weighted, wearable wireless EEG acquisition and analysis system to monitor the onsets and offsets of SMR features and integrate into a rehabilitation device or robot for controlling the ON

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and OFF of the movement of the device. Such a combination might largely alleviate the limitations on the degree of freedom of rehabilitation hardware or robot and allow more versatile rehabilitation processes.

II. METHODS

A table bike was connected to a newly developed high-quality wireless 4-ch EEG recording system and an EEG signal translation module to continuously record high-quality EEG from the scalp at C3/C4 region, extract the motor-imagery induced sensorimotor rhythm (SMR) feature in the EEG data, and translate the EEG feature into control signal to turn on/off the table bike. The wireless 4-ch EEG system samples EEG signal at 2K Hz with 24-bit resolution and transmits the digitized EEG signals wirelessly through Bluetooth 2.0 protocol to a signal acquisition module, such as a laptop or a smart phone. In addition, the wireless EEG device provides extremely high quality EEG signals with input referred noise of 1.5 uV, which outperforms most of the existing wireless EEG systems. The device itself weights about 22 g, suited for the applications in need of portable or even wearable EEG device.

The brain signal translation module receives digitized EEG signals from the wireless 4-ch EEG system and extracts the motor imagery induced event-related desynchronization of EEG sensorimotor rhythm as features. Finally, it translates result of detection into control commands to turn ON and OFF the table bike. The speed of the table bike movement was preprogrammed by the rehabilitation physician to fit the different requirements for different stroke patients. Although the current form factor of the table bike might not be optimal for neurorehabilitation process for stroke patients, the light-weighted wireless EEG and brain signal translation module can be easily adapted to any forms of rehabilitation devices. As a result, it can fit the requests of most rehabilitation physicians for devising the most suitable rehabilitation protocol for each individual stroke patient.

To evaluate the feasibility of the mind-controlled table bike, we conducted a pre-clinical test on 12 healthy normal subjects (5 female and aged 30 +/- 5 yrs., recruited from National Chiao Tung University campus) and one young (30 yr.) chronic stroke patient (6 mo. after stroke attack, recruited from China Medical University Hospital, CMUH). The experimental protocol was as follows: First, a 2-sec resting period was cued with a white cross at the center of a computer screen to ask subject to pay attention to the study as the task cue would be delivered any time soon. Then an execution cue (green disk) was delivered at the center of computer screen for 6 secs to ask subject to start motor imagery by imagining he/she is pushing the table bike forward using his/her hands without physical hand movements. If the subject could successfully move the table bike in the motor imagery trial, it was counted as a successful move; otherwise, it was counted as a failed move. The percentage of successful movement was used to evaluate the feasibility of the devised mind-controlled table bike. Informed consents were obtained from all subjects before the experiment. CMUH IRB approved the experimental protocol.

III. RESULT

For the 12 healthy normal subjects, the success rate was 80.06%. Among the 12 subjects, 7 of them had finished 4 additional runs of experiments in separate occasions (within two-month duration). The average success rates for all subjects were 82%, 86%, 92%, 67%, 79%, 74%, 74%, respectively. For the young stroke patient recruited from CMUH, fMRI of the same type of motor imagery task and diffusion tensor images (DTI) of this patient were used to determine the optimal scalp channel location. After the channel location had been determined, the patient participated in the motor imagery task and finished one session of experiment. The success rate of this patient was higher than 81%.

IV. DISCUSSION

In this study, we demonstrated an integrated work to interface a commercially available table bike for neurorehabilitation process with an ultra light-weighted, wearable wireless 4-ch EEG device and an EEG translation module to extract SMR signatures from the digitized EEG signals. Both the wearable wireless EEG module as well as the EEG translation module were designed and developed by our group. The output of the EEG acquisition and translation modules could be used to trigger ON and OFF the table bike for facilitating the BCI-based neurorehabilitation process. Finally, we conducted a motor imagery experiment to evaluate the feasibility of the devised BCI-based EEG-controlled table bike. The percentage of successfully detecting the SMR induced by the motor imagery and moving the table bike accordingly was used to rate the performance of the devised EEG-controlled table bike. Although the current study was mainly tested on the normal subjects, it is possible to translate the results of this work to clinical settings and help the patients after stroke attacks to regain the controls, at least in part, over their peripheral muscles.

The previous study showed that the accuracy of sensorimotor rhythm (SMR) feature detection might vary from subject to subject due partly to individual differences in the anatomies of sensorimotor cortex [2]. In our result, we did show individual differences in the performance in terms of success rate across different subjects. However, within the same subjects, the success rates were quite reproducible across different visits. It is also worth noting that the average success rate for this study was higher than the results as reported previously. This is mainly because that in our test result, only the ‘move’ condition was used and thus could bias the performance toward higher success rate for moving the device. That is, subjects and/or patients could maintain their performance to move the table bike without switching to the OFF mode for stopping movement. It was relatively easier for the subjects/patient to perform continuously the motor imagery task without alternating their mind between ‘move’ and ‘stop’ conditions as was reported in previous study. Nonetheless, the protocol with such a high success rate might be preferable from the standpoint for encouraging stroke patients and easing their training.

Although the reported wireless EEG-based neurorehabilitation device achieved such a high success rate among the normal subjects participated in this study, two major problems associated with the report device still largely concerned us: (1) what type of stroke patients can most benefit from the reported device, and (2) where is the best site on the scalp to place the EEG electrode such that the SMR features can be easily extracted for controlling the rehabilitation device? To answer the first question, we are currently incorporating the diffusion tensor imaging (DTI) technology to evaluate the integrity of the fiber tracts after stroke onset. We hypothesize that only the patients with the downstream fiber tracts intact or less contaminated by stroke attack might best benefit from the wireless EEG-based neurorehabilitation device. Thus, we are evaluating the integrity of the downstream fiber tracts of stroke patients and trying to establish a protocol for screening patients for the proposed rehabilitation process.

On the other hand, we are also testing the process to determine the best EEG electrode placement to extract the SMR features from the patients' scalp with either whole-head EEG or functional magnetic resonance imaging (fMRI) or even their combination. For EEG process, we are to wire patient with a 64-channel EEG device with whole-head coverage and run through the motor imagery and/or motor observation tasks (depending on if the patient is able to perform motor imagery task or not). As the C3 and C4 locations might become suboptimal after stroke attack, we will then search among the whole head and find out which channel(s) contains most promising SMR features for the further use. This can be the most straightforward way to figure out the best channel location(s) for the proposed neurorehabilitation process, but the process can be tedious given that patients might have some difficulties and concerns about capping for EEG recordings. Alternatively, we are to determine the best location(s) to place the EEG channels using fMRI examination, where patients are placed in an MRI scanner and asked to perform motor imagery and/or motor observation tasks. The scalp locations correspond to the fMRI activation patterns can be the target channel locations for extracting the SMR features. However, such an examination can be expensive and may add extra loading to the patients and their families. Incorporating the fMRI session with the regular follow-up examinations might be a potential solution.

Although the devised rehabilitation table bike with wearable wireless EEG frontend has been successfully applied to one young chronic stroke patient, it is still too early to draw a conclusion regarding the effectiveness of the rehabilitation device. First, given that the patient participated in this test was young and thus with above average motivation to involve in any possible training protocol so as to help her recover from the stroke attack as much as she can. As a result, the test on this patient only might favor the reported wireless EEG-based neurorehabilitation device. As a result, the conclusion can only be drawn after a large-scale clinical trial. In this end, we are to propose a clinical trial protocol to our hospital to conduct a large-scale clinical trial with well-controlled patient population, stroke phase, and protocol. In so doing, we hope to prove the effectiveness of the reported neurorehabilitation device on improving the recovery from the disabilities in the limbs caused by stroke attack.

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