Abstract—Phase-locked and non-phase-locked event-related oscillations and channel spectra during motor imagery with speed parameters (fast 4Hz and slow 1Hz) were investigated in the paper. EEG signals related to imagination of six tasks that involved three limbs (left and right index fingers and right toes) and two speeds were first separated from original EEG signals mixed with noises by ICA. Then, event-related EEG trials were superposed and averaged to get time domain average EEG that was decomposed by wavelet transform to investigate phase-locked event-related oscillations. Event-related EEG trials were also decomposed by wavelet transform respectively and then superposed and averaged to investigate non-phase-locked event-related oscillations. In addition, power spectra for selected channel were calculated by FFT. By these methods, the latency of 50~536ms and the low frequency band of 2.7~8Hz for an increase in power early after the event, latencies and frequency bands for significant different changes and a different degree decrease in power at high frequency band between fast and slow motor imagery, and ERD / ERS in a broad frequency band for selected channels were found. Simultaneously extracting phase-locked and non-phase-locked event-related oscillations in broadband range may be very important for acquiring complete information about event-related EEG during motor imagery with speed parameters. The research results may be used in feature extraction for brain-controlled robots interface (BCRI). In the based on brain cognitive robots control, this study is also expected to provide some degree continuous and fine control strategies for BCRI.

Keywords: Motor imagination with speed parameters; Phase-locked event-related oscillations; Non-phase-locked event-related oscillations; ERD/ERS; Brain-controlled robots interface (BCRI); brain-controlled robots (BCR)

I. INTRODUCTION

Brain-controlled robots interface (BCRI) based on brain cognition without muscle activity involvement is an interface technique between human brain and robots that not only can help severely motor-disabled persons to control their environment to improve the quality of their lives but also can assist healthy persons to accomplish certain tasks under specific circumstances [1]-[10]. The final objective of BCRI is to execute a certain extent continuous and fine control of robots as well as simple switch variables or directions control [11], [12]. It is necessary for this goal to not only identify the body type of motor imagery but also decode parameters variation in motor imagery with speed and force by BCRI.

There are more studies in identifying limb types of motor imagery than decoding motor imagery with speed and force parameters [13]-[15]. In addition, decoding subject’s mental intentions by measuring electrical activities of neurons or neuron ensemble or neural network based on invasive methods with potential injuries, which have very high spatial and temporal resolution, had been proved feasible and made progress [16],[17]. Decoding parameters variation of motor imagery by measuring EEG resulted from the activities of a large number of neurons based on non-invasive methods with electrodes placed on human scalp, which have low spatial resolution, is also one of the most challenging research works, and a few studies have showed the possibility [13]-[15]. However, how to improve the spatial resolution of EEG by inventing a new non-invasive measuring method and how to overcome the bottleneck of low spatial resolution of EEG by designing advanced signal processing technologies are still technical problems to be solved. Another solution is expected to propose appropriate methods to fuse high level task commands provided by BCRI and intelligent robot’s capability to achieve continuous and fine control of robots [18].

From research methods for event-related oscillations, average ERPs obtained by traditional time domain average superposition method that can't extract complete brainwave oscillation information only contains phase-locked evoked rhythm excluding non-phase-locked induced rhythm [19],[20]. Therefore, in this study, we based on a new experimental paradigms used in BCRI research proposed by us and EEG recorded from electrodes placed on the scalp to investigate simultaneously phase-locked event-related oscillations and non-phase-locked event-related oscillations during motor imagery at fast and slow.
II. METHODS

A. EEG Data Collecting

EEG signal acquisition was based on a special design paradigm that was oriented to continuous and fine control of robots. In the new paradigm, motor imagery was planned to involve different limbs and speeds and make subjects easily execute them. In the study, EEG data were acquired from 4 healthy subjects who were instructed to imagine tapping table (or left mouse button) with their left and right index fingers and tapping floor with their right toes at two speeds (fast 4Hz and slow 1Hz). The experimenter guided them to execute actual six tasks including Left Forefinger Fast (LFF), Left Forefinger Slow (LFS), Right Forefinger Fast (RFF), Right Forefinger Slow (RFS) Right Toes Fast (RTF), and Right Toes Slow (RTS) so as to obtain experience before signal acquisition. During the experiment, subjects performed motor imagination at a first-person perspective with recalling and feeling the kinesthetic experience of movement (first imaging). The six tasks were presented randomly to the subjects. During motor imagination, no visual feedback which indicated effect of task was provided to subjects who were asked to keep relaxation and avoid muscle activation, blink, slow eye movement, and facial muscle tension. Each subject took part in three sessions of 4 runs of 60 trials. Timing of a single trial is referenced in [21], [22].

We used a 64-channel digital DC EEG amplifier (Neuro Scan Labs, SynAmps 2) and signal band pass 0.05-100 Hz and a 50 Hz notch filter to acquire EEG signals (sampling frequency at 500Hz with a 24-bit A/D converter). Ag-AgCl electrodes (extended 10-20 system) and GND at forehead and REF at vertex were allocated in the experiment.

B. EEG Data Preprocessing

The objectives of preprocessing original EEG data lie in getting relatively clean task related EEG epoch signals for further analyses. The procedure of EEG data preprocessing is shown in Fig. 1. The analysis tool in this research is EEGLAB [23].

C. Phase-locked Event-related Oscillations Analysis

Channel selection based on the study involved the brain areas is very important because of the identification accuracy and practicality. The reasons we choose to channels for further analysis as follows.

On the one hand, almost all areas of the neocortex such as the prefrontal cortex and the primary somatosensory cortex (S1) as well as the cerebellum and subcortical motor nuclei outside the cortex play a role in the control of voluntary movements, but one of the brain areas dedicated to controlling these voluntary movements is the motor cortex [24]. The motor cortex can be divided into two groups with four main parts: (1) the primary motor cortex (or M1), which is responsible for generating the neural impulses controlling execution of movement and (2) the secondary motor cortices, including the posterior parietal cortex that is responsible for transforming visual information into motor command and the premotor cortex that is responsible for motor guidance of movement and control of proximal and trunk muscles of the body and the supplementary motor area (SMA) that is responsible for planning and coordination of complex movements such as those requiring two hands. The main cortices involved in the control of voluntary movements are shown in Fig. 2 [25]. Planning for any given movement is done mainly in the forward portion of the frontal lobe which receives information about the individual's current position from several other parts. Then it issues its commands to Area 6 (supplementary motor and premotor cortex area) which decides which set of muscles to contract to achieve the required movement, and then issues the corresponding orders to the primary motor cortex (Area 4) which in turn activates specific muscles or groups of muscles via the motor neurons in the spinal cord [24].

Figure 1. The procedure of EEG data preprocessing

Figure 2. The main cortices involved in the control of voluntary movements

On the other hand, not only actual voluntary motor is controlled and executed by motor cortex, some famous studies have shown that motor imagery can modify the neuronal activity in the primary sensorimotor areas in a very similar
way as observable with a real executed movement [26]. Features such as band power or adaptive autoregressive parameters are either extracted in bipolar EEG recordings overlaying sensorimotor areas or from an array of electrodes located over central and neighboring areas [26].

Based on the above comprehensive consideration, the channels C3, CZ, and C4 which overlap motor cortex area were selected to explore motor imagery with parameters as shown in Fig. 3.

The traditional average ERP technology was applied to get phase-locked event-related oscillations which in a certain extent can reflects the dynamic process of brain cognition in the study. In addition to this, the basic and key properties of non-stationary EEG signal are time domain local information. Therefore, time-frequency analysis can be a suitable tool for EEG [20]. The power spectral of average event-related EEG at frequency $f$ and time $t$ is estimated by short-time Fourier transform:

$$F(f,t) = \int_R f(\tau)g(\tau-t)e^{-i2\pi f \tau}d\tau$$

(1)

where $g_{f,t}(\tau) = g(\tau-t)e^{-i2\pi f \tau}$ as base function, window function $g(\tau-t)$ as time limit and shift, $e^{-i2\pi f \tau}$ as frequency limit. In the study, $F(f,t)$ is calculated by EEGLAB with a sinusoidal wavelet (short-time DFT) transformation in which the number of cycles is increased slowly with frequency to obtain better frequency resolution at higher frequencies than a conventional wavelet approach that uses constant cycle length [23].

The procedure for phase-locked event-related oscillation analysis using the EEGLAB V9_0_0_2b toolbox (at http://sccn.ucsd.edu/eeGLAB/) under MATLAB v7.6.0 (Mathworks, Natick, MA) as shown in Fig. 4.

**Figure 4.** The procedure for phase-locked event-related oscillations analysis

oscillations, the time-frequency power $F_k(f,t)$ of a single trial $k$ was calculated based on (1), and then event-related spectral perturbation (ERSP) as follows [23]:

$$ERSP(f,t) = \frac{1}{n} \sum_{k=0}^{n} [F_k(f,t)]^2$$

(2)

where $n$ is the total of trials. Significance of deviations from baseline power is assessed using a bootstrap method [23]. 0.01 is for the bootstrap significance level in the paper. Spectral power starts from -2000ms related to stimulus, baseline limits: -2000~1000ms, epoch time limits: -2000~4000 ms, and frequency limits: <50Hz. The procedure for non-phase-locked event-related oscillations analysis as shown in Fig. 5.

**Figure 5.** The procedure for non-phase-locked event-related oscillations analysis

**D. Non-phase-locked Event-related Oscillations Analysis**

In order to extract non-phase-locked event-related

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**III. RESULTS**

We used methods in section II to analyze EEG data from 4...
subjects and found similar results among subjects. Therefore, the representative results from subject1 are as follows.

A. The Results of Phase-locked Event-related Oscillations Analysis for Fast and Slow Motor Imagination.

Fig. 6 to 11 present the results of phase-locked event-related oscillation analysis for subject1 (subj1) during fast and slow motor imagery at the first view. Following TABLE I from the above figures shows latencies and low frequency bands for an increase in power early after the event under motor imagery modes. From TABLE I, common latency is about 50 ~ 536ms and frequency band is about 2.7~8Hz. This may be a very valuable result for BCRI based on fast and slow motor imagery.

In addition to the above important common early phase-locked event-related oscillation, the latencies and frequency bands for significant different changes in power between fast and slow motor imagery from the above figures are shown in TABLE II. These may be also very important results for further identification of a single trial.

B. The Results of Non-phase-locked Event-related Oscillations Analysis for Fast and Slow Motor Imagination

Fig. 12 to 17 shows the results of non-phase-locked event-related oscillation analysis for subject1 during fast and slow motor imagery at the first view. Surprisingly, we still can get phase-locked event-related components whose patterns (frequency band and latency) are very similar to the results by phase-locked event-related oscillation analysis whereas only their intensity becomes weaker than the later. Therefore, this may further show that phase-locked event-related component is a relatively stable oscillatory and can be used as classification feature for motor imagery at fast and slow. In
addition, Fig. 12 to 17 also shows an important result that a different degree decrease in power occurs at high frequency band.

**TABLE II. THE LATENCIES AND FREQUENCY BANDS FOR SIGNIFICANT DIFFERENT CHANGES IN POWER BETWEEN FAST AND SLOW MOTOR IMAGERY**

| Imagery mode & channel | Latency (ms) | Frequency band (Hz) | Power changes For brain activity |
|------------------------|-------------|---------------------|---------------------------------|
| RFF-C3/ RFS-C3         | -1000-0     | 6.6-20              | Incre/ Decre                    |
|                        | 1400-2900   | 2.7-13              | Incre/ Decre                    |
|                        | -1000-4000  | above 25            | Decre/ incre                     |
|                        | -1000-200   | 12-14.4             | incre /Decre                    |
|                        | 730-4000    | 2.7-12.5            | Decre/ incre                     |
| LFF-C4/ LFS-C4         | 750-4000    | 40-44.4             | Incre/ decre                    |
|                        | 1000-4000   | 26.8-32.5           | Decre incre                      |
|                        | -950-0      | 7.5-13.5            | Incre/ decre                    |
|                        | 800-4000    |                     |                                 |
| RTF-Cz/ RTS-Cz         | 750-4000    | 40-44.4             | Incre/ decre                    |
|                        | 1000-4000   | 26.8-32.5           | Decre incre                      |
|                        | -950-0      | 7.5-13.5            | Incre/ decre                    |
|                        | 800-4000    |                     |                                 |

a Incre/ decre for RTF-Cz/ RTS-Cz denote an increase in power for RTF-Cz and a decrease in power for RTS-Cz. Similar to the other.

**C. The Results of Channel Power Spectra Analysis.**

Fig. 18 and 19 show a decrease in power (ERD) at 12.2 (12) and 13.2 (13) Hz at left brain with blue color during motor imagery at fast and slow for right index finger. But a greater increase in power at these two frequencies at right brain with red color at slow than at fast occurs. In addition, in the case of higher frequency 22, 25.9(26), 28.8(29), 29.8(30), 34.2(34), 40Hz, an increase in power (ERS) at left brain for RFF but still ERD at right brain for RFS except for 40Hz.

Fig. 20 and 21 show a decrease in power (ERD) at 12.2 (12) and 13.2 (13) Hz at right brain with blue color during motor imagery at fast and slow for left index finger. A slight decrease in power at 22, 25.9(26), 28.8(29), 29.8(30), 34.2(34)
Hz at vertex area with light blue color and an increase in power at 40Hz at right brain for slow motor imagery whereas a decrease in power at 22, 25.9(26), 40Hz at right brain for fast motor imagery.

Fig. 22 and 23 show a decrease in power at 12.2 (12) and 13.2 (13) Hz at vertex area with blue color during motor imagery at fast and slow for right toes. An increase in power at 22, 40 Hz at left brain area during motor imagery at fast is not the same as motor imagery at slow.

In the study, based on a new experimental paradigm of fast and slow motor imagery involved three limbs used in BCRI research, we selected only three electrode locations C3, Cz, C4 of motor cortex area closely related to movement imagination, and then the latency of 50 ~ 536ms and the low

IV. CONCLUSION

Figure 18. Channel spectra and maps for subj1-first imaging-RFF

Figure 19. Channel spectra and maps for subj1-first imaging-RFS

Figure 20. Channel spectra and maps for subj1-first imaging-LFF

Figure 21. Channel spectra and maps for subj1-first imaging-LFS

Figure 22. Channel spectra and maps for subj1-first imaging-RTF

Figure 23. Channel spectra and maps for subj1-first imaging-RTS
frequency band of 2.7–8Hz for an increase in power early after the event were shown not only by phase-locked event-related analysis but also non-phase-locked event-related analysis. In addition, latencies and frequency bands for significant different changes in power between fast and slow motor imagery and a different degree decrease in power at high frequency band also were shown using these two kinds of methods. Also, we showed ERD and ERS in a broad frequency band for selected channels. This study will provide basic support for the realization of brain-controlled robots interface based on human brain cognitive and make continuous and fine control of robots by BCRI possible. The study also will provide methods and techniques support for the new research for the integration and fusion of human brain and robots. In the future BCRI research, we will control a humanoid robot in our laboratory by identification of single trial during fast and slow motor imagery.

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