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Research Paper

Online detection of amplitude modulation of motor-related EEG desynchronization using a lock-in amplifier: Comparison with a fast Fourier transform, a continuous wavelet transform, and an autoregressive algorithm

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HIGHLIGHTS

- We applied a lock-in amplifier (LIA) algorithm for online electroencephalogram (EEG) analyses.
- The LIA detected EEG motor-imagery-related amplitude modulation.
- We evaluated the detection delay, accuracy, and stability of the LIA.
- The LIA improved all three indices compared with an existing online algorithm.

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ABSTRACT

Background: Neurofeedback of event-related desynchronization (ERD) in electroencephalograms (EEG) of the sensorimotor cortex (SM1) using a brain–computer interface (BCI) paradigm is a powerful tool to promote motor recovery from post-stroke hemiplegia. However, the feedback delay attenuates the degree of motor learning and neural plasticity.
New method: The present study aimed to shorten the delay time to estimate amplitude modulation of the motor-imagery-related alpha and beta SM1-ERD using a lock-in amplifier (LIA) algorithm. The delay time was evaluated by calculating the value of the maximal correlation coefficient (MCC) between the time-series trace of ERDs extracted by the online LIA algorithm and those identified by an offline algorithm with the Hilbert transform (HT).
Results: The MCC and delay values used to estimate the ERDs calculated by the LIA were 0.89 ± 0.032 and 200 ± 9.49 ms, respectively.
Comparison with Existing Method(s): The delay time and MCC values were significantly improved compared with those calculated by the conventional fast Fourier transformation (FFT), continuous Wavelet transformation (CWT), and autoregressive (AR) algorithms. Moreover, the coefficients of variance of the delay time and MCC values across trials were significantly lower in the LIA compared with the FFT, CWT, and AR algorithms.
Conclusions: These results indicate that the LIA improved the detection delay, accuracy, and stability for estimating amplitude modulation of motor-related SM1-ERD. This would be beneficial for BCI paradigms to facilitate neurorehabilitation in patients with motor deficits.

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1. Introduction

Many studies have demonstrated that an electroencephalogram (EEG)-based brain–computer interface (BCI) can facilitate functional motor recovery in patients with hemiplegia due to stroke (Daly and Wolpaw 2008; Daly et al., 2009; Broetz et al., 2010; Prasad et al., 2010; Wang et al., 2010; Ang et al., 2011; Caria et al., 2011; Shindo et al., 2011; Ramos-Murguialday et al., 2013; Mukaino et al., 2014; Ang et al., 2015; Ono et al., 2015). This type of BCI often detects modulation of EEG oscillations (i.e., event-related desynchronization; ERD) over the primary sensorimotor area (SM1) induced by motor imagery; then, a visual display, motor-driven orthosis, or neuromuscular electrical stimulation provides visual/sensory feedback. Neurofeedback of SM1-ERD helps patients learn to activate cortical neurons, as SM1-ERD in the alpha (8–13 Hz) and beta bands (15–30 Hz) reflects cortical and spinal neuron excitability (Hummel et al., 2002) and gamma-aminobutyric acid (GABA)ergic intracortical disinhibition of cortical neurons (Takemi et al., 2013).

To detect modulation of motor-imagery-related SM1-ERD, some research groups have employed spectral analysis with fast Fourier transformation (FFT) (Shindo et al., 2011; Krusienski et al., 2012; Wang et al., 2013; Ge et al., 2014; Mukaino et al., 2014; Takemi et al., 2013, 2015; Ono et al., 2013, 2014, 2015), continuous wavelet transformation (CWT) (Cvetkovic et al., 2008; Al-Fahoum and Al-Fraihat, 2014), or an autoregressive (AR) model (Gunduz et al., 2012; Wang et al., 2012; Ramos-Murguialday et al., 2013). However, these algorithms are associated with a feedback delay >500 ms because of the time window needed to reliably estimate the ERD. Since visual feedback delay attenuates the effects of motor adaptation process (Kitazawa et al., 1995; Tanaka et al., 2011; Honda et al., 2012; Schween and Hegele, 2017), a BCI system with a short feedback delay would allow for more control of BCI in patients with motor deficits.

To reduce the feedback delay, the present study developed a novel online algorithm to estimate the amplitude modulation of motor-imagery-related SM1-ERD using a lock-in amplifier (LIA). The LIA is a very narrow, tunable filter that delivers amplitude and phase information of the carrier wave at a specific frequency in real time. Since the LIA enables reliable and point-by-point calculations of signal components with simple multiplication and filtering algorithms, it might be possible to develop a more reliable online algorithm to estimate the amplitude modulation of ERD with less delay.

To evaluate the performance of the online LIA algorithm, we calculated correlation coefficients between the ERD obtained by the online LIA algorithm and that obtained by the offline Hilbert transform (HT); the HT generates an ideal trace of amplitude modulation without a time delay. The accuracy and delay of the performance were determined by the value of the maximal correlation coefficient (MCC) and the time lag where MCC was detected. Last, we compared the accuracy and delay calculated by the online LIA algorithm with those calculated by the conventional online FFT, CWT, and AR algorithms in various time windows and overlap parameters.

2. Methods

2.1. Participants

Twenty healthy male participants (average age, 24.2 ± 2.9 years) were included in this study. All participants were right-handed, had no medical or psychological disorders (according to self-reports), and had normal or corrected-to-normal vision. All participants received a detailed explanation of the experimental procedures before the experiment, and written informed consent was obtained from all participants. The experimental protocol used in the study was in accordance with the Declaration of Helsinki and was approved by the ethics committee of Keio University.

2.2. Experimental paradigm

Each participant sat in a comfortable armchair and was asked to perform motor imagery (i.e., isometric right wrist extension). A 20-inch computer monitor was placed 60–90 cm in front of them. Each trial started with a presentation of the word “Rest” at the center of the monitor. After 5 s, the presented word changed to “Image,” which remained for 5 s. After the motor imagery phase, the screen was black for 3 s. In this phase, the participants were allowed to move freely. After that, the monitor showed the word “Rest,” and the next trial started. All participants completed 25 trials.

2.3. EEG recordings

EEG was recorded over the whole scalp using 128-channels (Geodesic Sensor Nets, Oregon, USA). The impedance of each electrode was maintained at less than 40 kΩ throughout the experiment (Ferree et al., 2001). The EEG signals were amplified and recorded at a sampling rate of 1000 Hz after DC remove, band-pass (3–70 Hz), and notch (50 Hz) filters with a fourth-order Butterworth filter by the Geodesic EEG System (Electrical Geodesics Incorporated [EGI], Oregon, USA). The EEG signals were spatially filtered with a large Laplacian filter, which subtracted the average of the next-nearest-neighbor electrodes (6 channels and 4 cm from the C3 electrode). Then, band-pass (3–70 Hz) and notch (50 Hz) filters with a fourth-order Butterworth filter were applied again via offline processing to segregate the entire brain-derived signal from noise. Last, a software-based calculation with FFT, CWT, AR, and LIA algorithms that emulated real-time processing was tested in this study (MATLAB 2016a; MathWorks, Massachusetts, USA).

2.4. Emulation of online ERD calculation with FFT

First, we used an FFT algorithm as the conventional method to estimate the alpha and beta amplitude modulations (Shindo et al., 2011; Mukaino et al., 2014; Takemi et al., 2013, 2015; Ono et al., 2013, 2015). To calculate the ERD, EEG data were processed using the following 4 steps: (1) segmentation of 0.1-, 0.25-, 0.5-, or 1-s time windows with 0, 50, 90, or 99% overlap; (2) power spectrum density (PSD) calculation by FFT algorithm with a Hanning window; (3) determination of a frequency of interest (FOI), which showed the most significant ERD over the alpha and/or beta bands by visual inspection; and (4) ERD transformation (Takemi et al., 2013). A reference time from 3 to 5 s in each resting phase was used to estimate ERD.

2.5. Emulation of online ERD calculation with CWT

Second, a CWT algorithm with a complex Morlet function was used as the conventional method to estimate the alpha and beta amplitude modulations (Cvetkovic et al., 2008; Al-Fahoum and Al-Fraihat, 2014). According to the commonly used parameter ranges of time windows and overlaps, ERD was calculated after the following 4 steps: (1) segmentation of 0.1-, 0.25-, 0.5-, or 1 s time windows with 0, 50, 90, or 99% overlap; (2) PSD calculation by the CWT algorithm with a complex Morlet function; (3) determination of an FOI, which showed the most significant ERD over the alpha and/or beta bands by visual inspection; and (4) ERD transformation. A reference time from 3 to 5 s in each resting phase was used to estimate ERD.