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Single-Trial Classification and Evaluation of Hemodynamic Responses during Passive and Active Exercises for Neurorehabilitation

Chang-Hee Han[1*], Han-Jeong Hwang[2], Jeong-Hwan Lim[1], and Chang-Hwan Im[1†]
[1] Department of Biomedical Engineering, Hanyang University, Seoul, Republic of Korea.
[2]Department of Computer Science, Technical University of Berlin, Berlin, Germany.
Zeros8706@bme.hanyang.ac.kr*, ich@hanyang.ac.kr†

Abstract

In this study, we recorded and evaluated hemodynamic responses induced by conventional passive exercise for neurorehabilitation and combined exercise strategy (passive exercise with active motor execution or motor imagery). Functional near infrared spectroscopy (fNIRS) was recorded while eight healthy subjects conducted three different tasks (passive motor execution alone, passive motor execution with motor imagery, and passive motor execution with active motor execution). From the results, stronger and broader activation around the sensorimotor cortex was observed when subjects performed the combinatory strategies. Results of single-trial pattern classification showed the classification accuracy of more than 70%, demonstrating that fNIRS could be used as a potential tool to monitor how actively the users engaged in the combinatory neurorehabilitation strategy.

1 Introduction

Patients with motor impairment due to central nervous system diseases such as stroke and Parkinson's disease have difficulties in their daily-life activities, and many of them are not able to perform basic body movements without caregivers or assistive devices. To now, many researchers have developed various neurorehabilitation strategies for recovering their damaged motor functions.

Recently, researchers have shown that a combinatory neurorehabilitation strategy that simultaneously uses both passive and active exercise can dramatically enhance the outcomes of conventional passive exercises. For example, Joa et al. compared brain activations induced by the passive exercise (passive motor execution by functional electrical stimulation (FES)), the active exercise (voluntary contraction), and combination of both using functional magnetic resonance imaging (fMRI) (Joa, 2012), and demonstrated that the combination of the passive and active exercises may be more effective for successful neurorehabilitation.

Nevertheless, this combinatory strategy has a critical limitation in that the practitioners cannot know how actively the patients perform the active motor execution or motor imagery during passive exercise. Therefore, it is needed to monitor patients' active engagement in the rehabilitation program.

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† Masterminded and created the first stable version of this document

In this study, we investigated whether functional near-infrared spectroscopy (fNIRS) could be used to evaluate whether the users actively performed active motor execution or motor imagery during passive exercise. To this aim, we compared the concentration changes of oxygenated hemoglobin (oxy-Hb) induced by "passive exercise alone" and "combinatory strategies". We then classified the "passive exercise alone" and the "combinatory strategies" using single-trial fNIRS data.

2 Methods

2.1 Subjects

A total of eight healthy subjects (six males and two females, 24-30 years old) were enrolled in our study. All subjects were right-hander and had normal or corrected-to-normal vision. None of them had a previous history of neurological, psychiatric, or other severe diseases that might affect the experimental results.

2.2 Experimental setup and procedure

We used a commercial multi-channel NIRS instrument (FOIRE-3000 from Shimadzu Corporation, Kyoto, Japan) for recording cortical activity. The absorptions of three wavelengths (780, 805, and 830 nm) of near-infrared light were acquired at a sampling rate of 10 Hz and then transformed into concentration changes of oxygenated hemoglobin (oxy-Hb), deoxygenated hemoglobin (deoxy-Hb), and total hemoglobin (total-Hb) using the modified Beer-Lambert law (Delpy 1988). The system detected changes in the cortical concentration levels (mM cm) of oxy-, deoxy- and total-Hb. In this study, we used 40 channels with twelve illuminators and thirteen detectors. The international 10-20 system was adopted to locate the optodes to cover whole motor-related areas such as premotor cortex, supplementary motor cortex (SMA), primary motor cortex (M1), and posterior parietal cortex. During the experiments, all subjects performed three different tasks. First task was "passive exercise alone" (passive motor execution: PME). In this task, subject's right index finger was automatically moved by a finger rehabilitation device regardless of the subject's movement intention. Second task was "combinatory strategy 1" (passive motor execution with motor imagery: PME+MI). In this task, the subjects simultaneously performed PME and motor imagery of their right index finger. Third task was "combinatory strategy 2" (passive motor execution with active motor execution: PME+AME). The subjects performed both passive motor execution and active motor execution of their right index finger at the same time. One trial consisted of a task period of 10 seconds and a rest period of 10-15 seconds, and all subjects repeated each task 40 times.

2.3 Data analysis

The concentration changes of oxy-, deoxy-, and total-Hb were processed using various preprocessing methods. First, we applied a common average reference (CAR) spatial filter to remove respiratory and cardiac noises. Then, the preprocessed data were band-pass filtered using 4^{th}-order zero phase Butterworth filter with a pass-band of 0.01-0.1 Hz to reduce physiological noises. The filtered data were divided into 20-s epochs, including the task period from 0 to 10 s and the rest period from 10 to 20 s. For the baseline correction, we used a base reset method, which adjusts a first sample to the zero point (Lee, 2012). We then conducted statistical analysis and single-trial pattern classification. First, to evaluate the statistical differences among hemodynamic responses elicited by the "passive exercise alone (PME)" or the "combinatory strategy 1 (PME+MI) and 2 (PME+AME)", we performed Friedman test (significant level: $p < 0.05$) and Wilcoxon signed rank test (post-hoc analysis using Bonferroni corrected p-value). Through this procedure, we selected only statistically

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meaningful channels among 40 channels. Second, we classified the "passive exercise alone" and the "combinatory strategies" using the hemodynamic responses of the selected channels. We used five moving windows with different windows sizes of 1, 2, 4, 5, and 10 seconds and extracted features by moving the windows along the time axis with 50% overlap. Five features (mean, variance, kurtosis, skewness, and slope) were evaluated for each moving window. The linear bayes normal classifier implemented in the PRtools package was used for the binary classification (Duing, 2000). The 10 by 10 cross-validation was performed for the estimation of classification accuracy.

3 Results

Figure 1 shows topographic maps of oxy-Hb concentration changes induced by the "passive exercise alone" and the "combinatory strategies". It could be observed from the figures that the oxy-Hb concentration changes during both "combinatory strategies" were stronger and broader than that during "passive exercise alone".

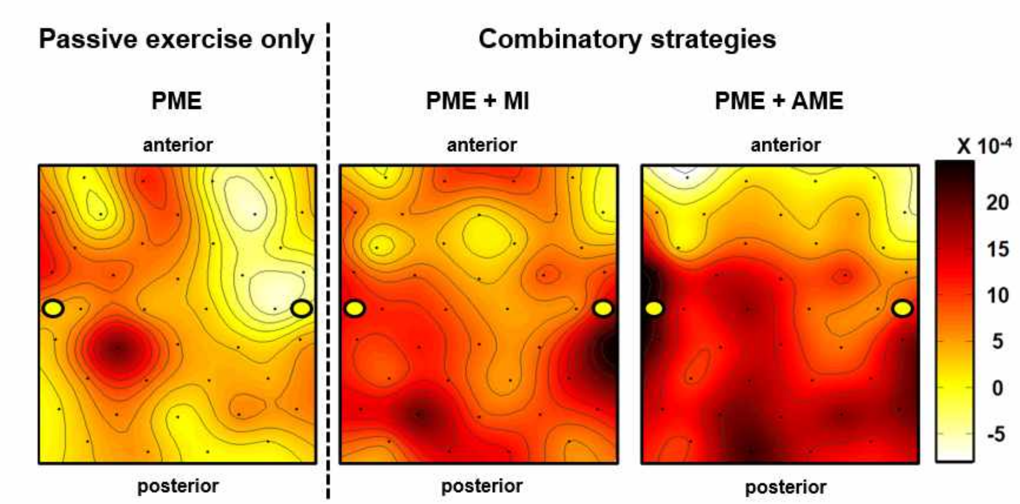

Figure 1: Topographic map of oxy-Hb concentration changes in each task. Left and right yellow circles reprecent locations of C3 and C4, respectively.

Table 1 shows the results of the single-trial pattern classification. The "passive exercise alone" and the "combinatory strategies" could be classified with classification accuracy larger than 70%, which is high enough to be used as an indicator to evaluate whether the users actively performed active motor execution or motor imagery during passive exercise (Choularton, 2004).

Subject No.	Classification accuracy (%)	
	PME vs PME + MI	PME vs PME + AME
1	69.4	70.3
2	73.4	74.1
3	77.5	72.3
4	70.9	68.4
5	73.4	73.4
6	67.0	73.4
7	75.0	73.4
8	67.4	68.5
Mean	71.8	71.7

Table 1: Results of single-trial pattern classification

4 Discussion and Conclusion

In the present study, we investigated whether fNIRS could be used to evaluate how actively users performed active motor execution or imagery during passive exercise. To the best of our knowledge, the classification of neural responses elicited by "passive exercise" and "combinatory strategies" was not reported before. Our experimental results showed stronger and broader neural activation during the "combinatory strategies" than the conventional "passive exercise alone". In addition, two different neurorehabilitation strategies could be classified with the classification accuracy larger than 70%, demonstrating that the user's active engagement in the neurorehabilitation might be successfully monitored using fNIRS.

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