Development of a New Rehabilitation System Based on a Brain-Computer Interface Using Near-Infrared Spectroscopy

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Abstract We describe the set-up for an electrical muscle stimulation device based on near-infrared spectroscopy (NIRS), designed for use as a brain-computer interface (BCI). Employing multi-channel NIRS, we measured evoked cerebral blood oxygenation (CBO) responses during real motor tasks and motor-imagery tasks. When a supra-threshold increase in oxyhemoglobin concentration was detected, electrical stimulation (50 Hz) of the biceps brachii muscle was applied to the side contralateral to the hand grasping task or ipsilateral to the motor-imagery task. We observed relatively stable and reproducible CBO responses during real motor tasks with an average accuracy of 100%, and during motor imagery tasks with an average accuracy of 61.5%. Flexion movement of the arm was evoked in all volunteers in association with electrical muscle stimulation and no adverse effects were noted. These findings suggest that application of the electrical muscle stimulation system based on a NIRS-BCI is non-invasive and safe, and may be useful for the physical training of disabled patients.

1 Introduction

Brain–computer interface (BCI) systems have been developed to allow control of computers or external electrical devices based on detection of brain activity alone. Previous investigations have focused on applying BCI systems as supportive tools to assist locomotion, volitional movements of the hands, and communication for disabled patients (such as those with stroke, spinal cord injury, amyotrophic lateral sclerosis, and movement disorders) [1, 2]. BCI systems may also be applicable to assist rehabilitation of chronic stroke patients [3].Current BCI systems employ surface electroencephalography (EEG) [4, 5],

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electrocorticography (ECoG) and intracranial implanted electrodes [6], magnetoencephalography (MEG) [3, 7], blood-oxygen-level dependent functional MRI [8], and near-infrared spectroscopy (NIRS) [9, 10] as signal acquisition modalities. NIRS is a noninvasive optical technique used to measure concentration changes in oxyhemoglobin and deoxyhemoglobin in cerebral vessels based on the characteristic absorption spectra of hemoglobin in the near-infrared range [11, 12]. Recently, NIRS has been suggested to be a promising signal acquisition tool for BCI because of its handiness, portability, good spatial resolution, metabolic specificity, and suitability for continuous measurement of brain activity changes with high time resolution [9, 10]. A disadvantage, however, is that NIRS is slow to operate because of the intrinsic latency of the brain hemodynamics [10]. Therefore we consid-

2.2 Experimental Procedure

Hand grasping was performed as a motor task, and self-paced imagination of hand grasping was also performed as a motor-imagery task. A trial consisted of a baseline period of 10 s and a hand-grasping/motor-imagery task period of 20s. Each session consisted first of 2 trials as a preparation stage for threshold learning with data analysis software, and then the following trials as a NIRS-BCI working stage (Fig. 2). Hand-grasping and motor-imagery data were collected in separate sessions.

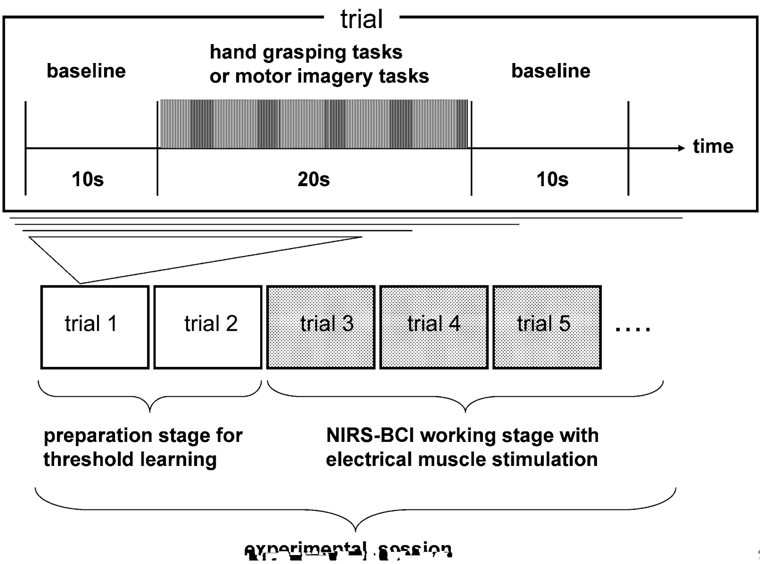

Fig. 2 Experimental protocol for hand grasping and motor imagery to elicit NIRS signals from subjects. A trial consisted of a baseline block of 10 s and a hand-grasping/motor-imagery task block of 20 s (*upper panel*). Each session consisted first of 2 trials as the preparation stage for threshold learning and then serial trials as the NIRS-BCI working stage with electrical muscle stimulation (*lower panel*). Hand-grasping and motor-imagery data were collected in separate sessions

We used a continuous-wave multi-channel NIRS instrument (OMM 2000, Shimadzu Corporation, Japan) for two-dimensional imaging of the changes in concentration of oxyhemoglobin, deoxyhemoglobin, and total hemoglobin (total hemoglobin = oxyhemoglobin + deoxyhemoglobin) in the activated cortices of the bilateral frontal lobes, as used in previous NIRS studies [13]. This system consists of 16 light-source fibers and 16 detectors, resulting in 48 source-detector pairs; each light source has 3 laser diodes with wavelengths of 780, 805, and 830 nm [14]. These probes were placed on the left and right hemispheres on the subject's head, above the motor cortex, around the C3 (left hemisphere) and

C4 (right hemisphere) areas (International 10–20 System). The distance between probes was 30 mm, and an area measuring 90 × 90 mm^2 was covered.

2.3 NIRS-BCI Signal Analysis

NIRS data were transferred from the OMM 2000 to a workstation via an Ethernet online connection, and NIRS data analysis was performed employing custom software for NIRS-based BCI (from Shimadzu Corporation, Japan) implemented in Matlab (Mathworks, Sherborn, MA, USA). In each subject, several (1∼3) channels in which a suitable hemodynamic response was obtained during the hand-grasping task or motor-imagery task was selected for operating decision making in NIRS-BCI. In the first two trials of each session, the changes of oxyhemoglobin were normalized in accordance with the maximum value of oxyhemoglobin, and the threshold level for "BCI-on" was determined as 0.3 (30%) of the maximum value. In the following trials in each session, the BCI-on signal command was outputted from the workstation during supra-threshold increase in cerebral regional oxyhemoglobin, and was sent to the electrical muscle stimulation device. When oxyhemoglobin fell below the threshold level, output of the BCI-on signal was interrupted.

2.4 Electrical Muscle Stimulation

This electrical muscle stimulation system based on NIRS-BCI provides a passive elbow joint movement, and assists the subject in exercising the muscle. Using a surface electrode, electrical stimulation (50 Hz) of the biceps brachii muscle was applied to the side contralateral to the grasping task or ipsilateral to the motor-imagery task. In each subject, stimulation intensity was appropriately arranged to be able to evoke flexion movement of the arm without pain.

3 Results and Discussion

We observed relatively stable and reproducible hemodynamic responses. In all subjects, NIRS showed a decrease of Deoxy-Hb associated with increases of Oxy-Hb and total Hb in the primary motor cortex contralateral to the hand-grasping (Fig. 3a) and motor-imagery task performance (Fig. 3b). Average working accuracy of the NIRS-BCI system was 100% in the hand-grasping task, and 61.5% in the motor-imagery task (Table 1). When the NIRS-BCI system sent the "on-signal" to the electrical muscle stimulator, continuous flexion movement of the forearm was evoked in all subjects in association with stimulation of the biceps brachii muscle. In the cerebral hemisphere

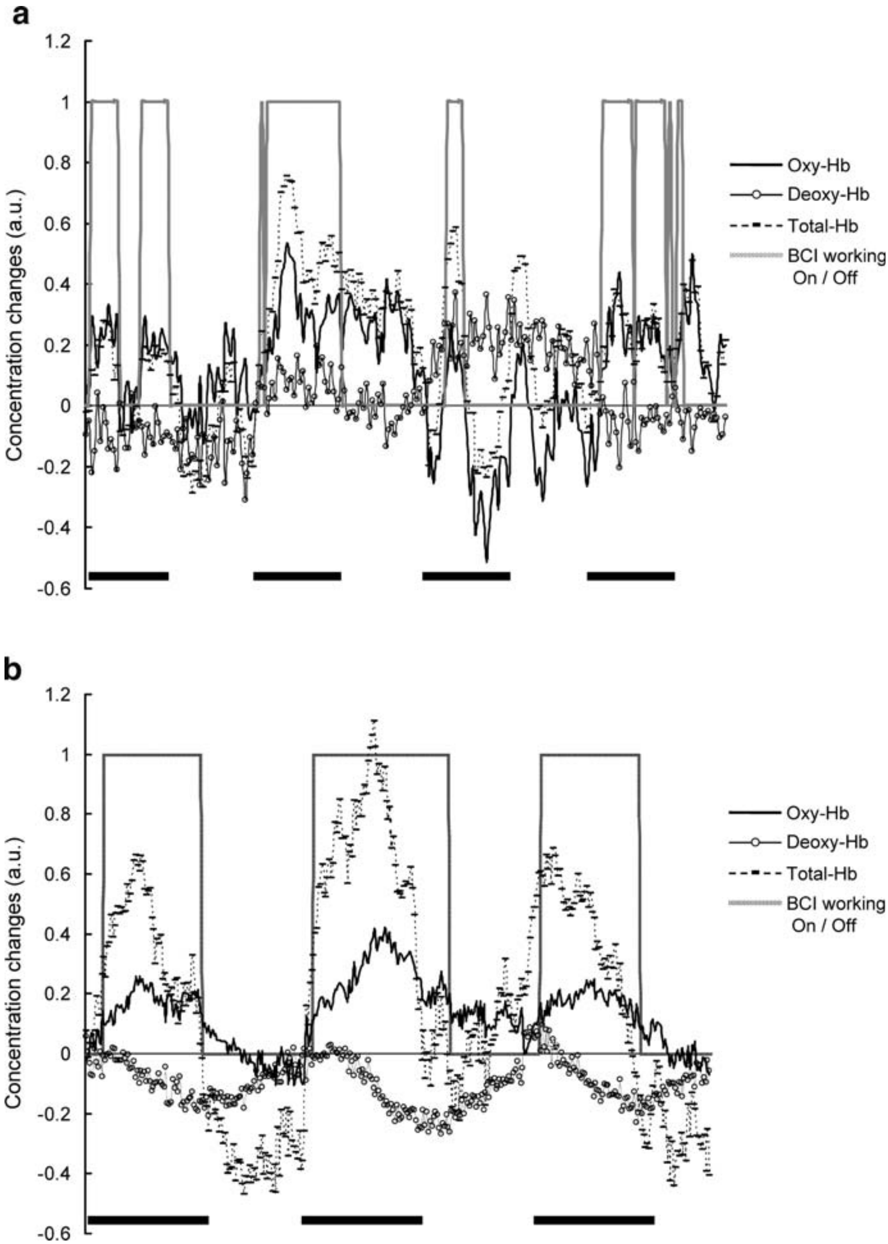

Fig. 3 Typical examples of NIRS parameter changes during hand-grasping (a) and motor-imagery tasks (b). The ordinates indicate concentration changes of oxyhemogrobin (Oxy-Hb), deoxyhemoglobin (Deoxy-Hb), and total hemoglobin (Total-Hb) in arbitrary units (a.u.). Thick horizontal bars indicate the period of hand-grasping tasks or motor-imagery tasks

contralateral to the motor imagery task, hemodynamic responses induced by muscle stimulation were not definitely detected. No adverse effects were noted. These findings suggest that application of an electrical muscle stimulation

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