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The cortical activation pattern during bilateral arm raising movements

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Abstract

Bilateral arm raising movements have been used in brain rehabilitation for a long time. However, no study has been reported on the effect of these movements on the cerebral cortex. In this study, using functional near infrared spectroscopy (fNIRS), we attempted to investigate cortical activation generated during bilateral arm raising movements. Ten normal subjects were recruited for this study. fNIRS was performed using an fNIRS system with 49 channels. Bilateral arm raising movements were performed in sitting position at the rate of 0.5 Hz. We measured values of oxyhemoglobin and total hemoglobin in five regions of interest: the primary sensorimotor cortex, premotor cortex, supplementary motor area, prefrontal cortex, and posterior parietal cortex. During performance of bilateral arm raising movements, oxyhemoglobin and total hemoglobin values in the primary sensorimotor cortex, premotor cortex, supplementary motor area, and prefrontal cortex were similar, but higher in these regions than those in the prefrontal cortex. We observed activation of the arm somatotopic areas of the primary sensorimotor cortex and premotor cortex in both hemispheres during bilateral arm raising movements. According to this result, bilateral arm raising movements appeared to induce large-scale neuronal activation and therefore arm raising movements would be good exercise for recovery of brain functions.

Key Words: *nerve regeneration; neuronal activation; bilateral arm raising; functional NIRS; motor control; corticospinal tract; corticoreticulospinal tract; neural regeneration*

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Introduction

Various therapeutic modalities, including therapeutic exercise for physical therapy intervention, neurotrophic drugs, procedures for relieving spasticity, neuromuscular electrical stimulation for the affected extremities and repetitive transcranial magnetic stimulation, have been used in rehabilitation for patients with brain injury (Feeney et al., 1982; Bobath, 1990; Scheidtmann et al., 2001; Carr and Shepherd, 2003; Takeuchi et al., 2005; Kwon and Jang, 2012; Lee and Jang, 2012). Among these modalities, therapeutic exercise has long been a basic and essential modality of physical therapy for brain rehabilitation (Bobath, 1990; Carr and Shepherd, 2003). The focus of therapeutic exercise has been on relieving spasticity of affected extremities, or improving functional activity (Bobath, 1990; Carr and Shepherd, 2003). Consequently, little is known about the direct effect of therapeutic exercise on the brain. This information can be useful for development of scientific therapeutic strategies based on the concept of brain plasticity; therefore, clarification of this effect of therapeutic exercise would be important for patients with brain injury (Bach-y-Rita, 1981; Kaplan, 1988).

Bilateral arm raising movements have been used in therapeutic exercise of brain rehabilitation for a long time (Bobath, 1990). In addition, it is one of the most commonly recommended bedside exercises during rehabilitation in patients with brain injury (Bobath, 1990). This movement is known to be effective in practice of range of motion exercise of upper extremity, improving awareness of equality of both hands, and relieving flexor spasticity of upper extremity (Bobath, 1990). However, no study has reported on the effect of these movements on the cerebral cortex which concerned with motor planning and execution. Among functional neuroimaging techniques, functional near infrared spectroscopy (fNIRS), which measures hemodynamic changes in the cerebral cortex, would be appropriate for research on the cortical effect of bilateral arm raising movement because fNIRS is less sensitive to motion artifact (Miyai et al., 2001; Perrey, 2008; Holtzer et al., 2011; Leff et al., 2011; Karim et al., 2012; Kurz et al., 2012).

In the current study, using fNIRS, we attempted to investigate cortical activation generated during bilateral arm raising movements.

Subjects and Methods

Participants

Ten healthy subjects (eight males, two females; mean age 29.40 ± 1.43 years, range 25–32 years) with no history of neurological, physical, or psychiatric illness were recruited for this study through volunteer recruitment notice. All subjects understood the purpose of the study and provided written, informed consent prior to participation. The study protocol was approved by our Institutional Review Board (approval No. YUH-12-0419-D12).

Bilateral arm raising movements

All subjects were asked to sit comfortably on a chair in an upright position. The subjects were instructed to extend the elbow fully and clasp their fingers with the direction of their palms facing outward on the thigh, and raise their hands up to the horizontal level with the uppermost part of the head, and then return to the thigh. The motor task was performed from the knee to vertical position (**Figure 1**). Using a block paradigm design (three cycles; resting [20 seconds]-motor task [20 seconds]-resting [20 seconds]-motor task [20 seconds]-resting [20 seconds]-motor task [20 seconds]), bilateral arm raising movements were performed at a frequency of 0.5 Hz under metronome guidance. The motor task was repeated three times at intervals of 5 minutes for the rest between each motor task.

fNIRS

The fNIRS system (FOIRE-3000; Shimadzu, Kyoto, Japan), with continuous wave laser diodes with wavelengths of 780, 805, and 830 nm, was used for recording of cortical activity at a sampling rate of 10 Hz; we employed a 49-channel system with 30 optodes (15 light sources and 15 detectors). Based on the modified Beer-Lambert law, we acquired values for oxyhemoglobin (HbO) and total hemoglobin (HbT) following changes in levels of cortical concentration (Cope and Delpy, 1988). The international 10/20 system, with Cz (cranial vertex) located beneath the 25th channel, was used for positioning of optodes. A stand-alone application was used for spatial registration of the acquired 49 channels on the Montreal Neurological Institute (MNI) brain based on the 25th channel on the Cz (Cope and Delpy, 1988).

The software package NIRS-SPM (http://bisp.kaist.ac.kr/NIRS-SPM) implemented in the MATLAB environment (The Mathworks, Natick, MA, USA) was used in analysis of fNIRS data. Gaussian smoothing with a full width at half maximum (FWHM) of 2 seconds was applied to correction of noise from the fNIRS system (Cope and Delpy, 1988). The wavelet-minimum description length based detrending algorithm was used for correction of signal distortion due to breathing or movement of the subject (Ye et al., 2009). SPM *t*-statistic maps were computed, and significant value of HbO and HbT were considered significant at the threshold of $P < 0.05$ (with expected Euler characteristics) (Ye et al., 2009; Li et al., 2012).

Regions of interest (ROIs)

Based on the Brodmann area (BA) and anatomical locations of brain areas, we designated five ROIs in the bilateral hemispheres as follows: the primary sensorimotor cortex (SM1) (BA1, 2, 3, 4), supplementary motor area (SMA) (medial boundary: midline between the right and left hemispheres, lateral boundary: the line 15 mm lateral from the midline between the right and left hemispheres), premotor cortex (PMC) (BA6 except for the SMA), prefrontal cortex (PFC) (BA 8,9), and posterior parietal cortex (PPC) (BA 5,7) (Brodmann, 1909; Afifi and Bergman, 2005). In addition, we divided the ROIs of the SM1 into two areas according to the homunculus: the somatotopic areas for arm and leg, respectively (Afifi and Bergman, 2005) (**Figure 2A**). Values for HbO and HbT were estimated from each channel of the five ROIs during performance of bilateral arm raising movements. Subsequently, using the NIRS-SPM, HbO and HbT values of each ROI were acquired based on the individual general linear model (GLM) analysis results; the values indicate the relative change of HbO and HbT between resting and motor task phase.

Data analysis

SPSS 20.0 software (IBM, Armonk, NY, USA) was used in performance of data analysis. The Kruskal-Wallis test with *post hoc* Mann-Whitney *U* test was used for determination of differences in HbO and HbT values between ROIs. Results were considered significant when *P* value was < 0.05.

Results

Based on the GLM analysis results, HbO and HbT values were acquired in each ROI; HbO and HbT values indicate relative change between resting and motor task phases during bilateral arm raising movements. HbO and HbT values were significantly higher in the SM1 (total: HbO = 0.0063, HbT = 0.0046; arm: HbO = 0.0069, HbT = 0.0057; leg: HbO = 0.0056, HbT = 0.0045), PMC (HbO = 0.0087, HbT = 0.0055), SMA (HbO = 0.0055, HbT = 0.0050) and PFC (HbO = 0.0058, HbT = 0.0049) than in the PPC (HbO = 0.0029, HbT = 0.0021) ($P < 0.05$) (**Table 1**). In comparisons between all SM1, PMC, SMA, and PFC, we observed no significant difference in HbO and HbT values ($P > 0.05$). In addition, no significant differences in HbO and HbT values were observed between the right and left hemispheres ($P > 0.05$).

t-statistic maps from HbO and HbT (corrected with expected EC, $P < 0.05$) values showed significant activation in bilateral SM1, PMC, and PFC during bilateral arm raising movements. **Figure 2B** showed higher activation in the arm somatotopic areas of the SM1 and PMC than in other ROIs in both hemispheres.

Discussion

In the current study, we measured HbO and HbT values as indices of neuronal activation in which neuronal activity was measured indirectly through detection of hemodynamic changes of the underlying cerebral cortex (oxygen consumption by neuronal cells) (Irani et al., 2007; Perrey, 2008). Cortical activation of the SM1, PMC, SMA and PFC was greater than that of PPC in both hemispheres. The results described above generally coincided with the results of *t*-statistic maps. Our results appear to suggest that performance of bilateral arm raising movements can activate bilateral SM1 and PMC. Consequently, bilateral arm raising movements appeared to require large-scale neuronal recruitment; therefore, it would be good exercise for brain activation.

Motor control in the human brain between musculature of

Table 1 Comparison of oxyhemoglobin and total hemoglobin values between posterior parietal cortex and other regions of interests

	SM1						
	Total	Arm	Leg	PMC	SMA	PFC	PPC
HbO (M)	0.0063±0.0032*	0.0069±0.0048*	0.0056±0.0034*	0.0087±0.0045*	0.0055±0.0030*	0.0058±0.0036*	0.0029±0.0028
HbT (M)	0.0046±0.0028*	0.0057±0.0041*	0.0045±0.0034*	0.0055±0.0025*	0.0050±0.0034*	0.0049±0.0024*	0.0021±0.0024

Values are expressed as the mean ± standard deviation. *$P < 0.05$, *vs*. PPC (Kruskal-Wallis test followed by *post hoc* Mann-Whitney *U* test). HbO: Oxyhemoglobin; HbT: total hemoglobin; SM1: primary sensorimotor cortex; PMC: premotor cortex; SMA: supplementary motor area; PFC: prefrontal cortex; PPC: posterior parietal cortex.

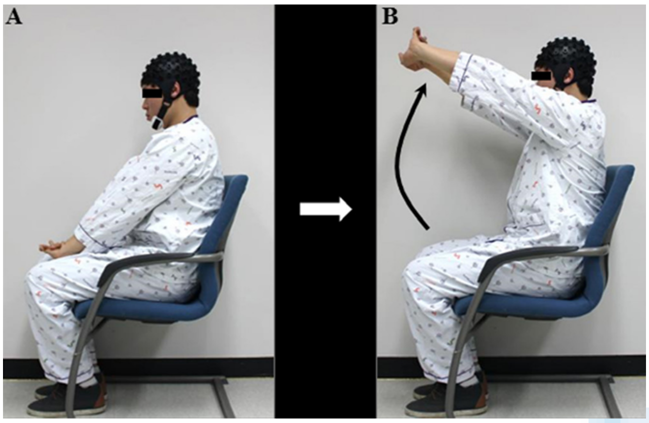

Figure 1 Arm raising movement for the therapeutic exercise.
The subjects were instructed to extend the elbow fully and clasp their fingers with the direction of their palms facing outward on the thigh (A), and to raise their hands up to the horizontal level with the uppermost part of the head (B), and then return to the thigh.

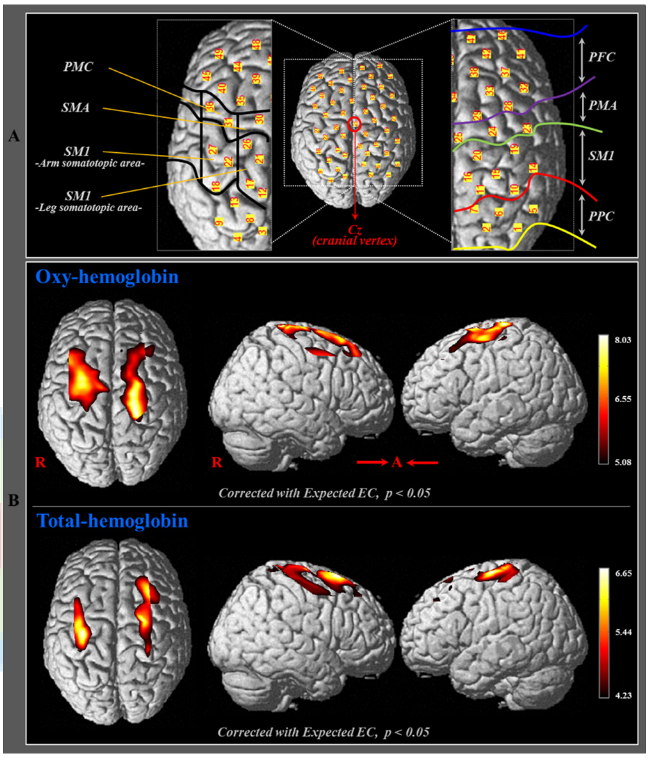

Figure 2 Results of oxyhemoglobin (HbO) and total hemoglobin (HbT) values during bilateral arm raising movements in healthy participants.
(A) Five regions of interest based on the Brodmann area (BA) and anatomical location of areas of the brain. The primary sensorimotor cortex (SM1): BA1, 2, 3, and 4; supplementary motor area (SMA); premotor cortex (PMC); prefrontal cortex (PFC): BA8 and 9; posterior parietal cortex (PPC): BA5 and 7; the arm somatotopic area of the SM1 (medial boundary: medial margin of the precentral knob, lateral boundary: lateral margin of the precentral knob); the leg somatotopic area of the SM1 (medial boundary: longitudinal fissure, lateral boundary: medial margin of the precentral knob). (B) Group-average *t*-statistic maps of HbO and HbT during performance of bilateral arm raising movements using NIRS-SPM software (corrected with expected Euler characteristics, $P < 0.05$).

proximal and distal joints has been suggested to differ (Freund and Hummelsheim, 1984, 1985; York, 1987; Davidoff, 1990; Matsuyama et al., 2004; Mendoza and Foundas, 2007; Jang, 2009; Yeo et al., 2012). Musculature of distal joints, particularly the hand, is controlled by the lateral corticospinal tract (York, 1987; Davidoff, 1990; Jang, 2009; Cho et al., 2012). By contrast, control of musculature of proximal joints, such as shoulder and hip, by the corticoreticulospinal tract has been suggested (Freund and Hummelsheim, 1984, 1985; York, 1987; Matsuyama et al., 2004; Mendoza and Foundas, 2007; Yeo et al., 2012). The corticospinal tract and corticoreticulospinal tract are known to originate mainly from the primary motor cortex and the PMC, respectively (Russell and Demyer, 1961; Jane et al., 1967; Matsuyama et al., 2004; Yeo et al., 2012). Therefore, our results showing bilateral arm SM1 and PMC were activated without difference indicate that the corticospinal tract and corticoreticulospinal tract were activated equally by performance of bilateral arm raising movements. The PMC is the cerebral area involved in planning, preparation, and initiation of movement, along with the SMA as a secondary motor area (Halsband et al., 1994; Leonard, 1998). Consequently, activation of the PMC appears to be related to motor planning for performance of bilateral arm raising movements.

Since introduction of functional neuroimaging techniques, many studies have reported on brain activation patterns during execution of various movements in normal subjects and patients with stroke (Miyai et al., 2001; Luft et al., 2002; Kapreli et al., 2006; Perrey, 2008; Holtzer et al., 2011; Kim et al., 2011; Leff et al., 2011; Karim et al., 2012; Kurz et al., 2012). In 2013, using functional magnetic resonance imaging, Craciunas et al. (2013) suggested that stroke patients with poor proximal recovery showed low level of cortical activation in the SM1 and PMC (Craciunas et al., 2013). In 2015, using functional magnetic resonance imaging, Pundik et al. (2015) reported increment of cortical activation in contralesional and bilateral primary motor cortex and premotor cortex following recovery of proximal arm function in patients with stroke.

These results appear to be compatible with the results of the current study, which showed increased cortical activation in the SM1 and PMC by proximal joint movement. We believe that the results of this study would be helpful for conduct of research on brain rehabilitation. In addition, fNIRS is a good tool for use in research on the effects of therapeutic exercise on the brain, which is employed in the field of brain rehabilitation. However, this study is limited by a small sample size. In addition, the limitation that this study could not include patients with brain injury should be considered. Further studies about the clinical implications of these findings for patients with brain injury are required.

Declaration of patient consent: *The authors certify that they have obtained all appropriate patient consent forms. In the form the patient(s) has/have given his/her/their consent for his/her/their images and other clinical information to be reported in the journal. The patients understand that their names and initials will not be published and due efforts will be made to conceal their identity, but anonymity cannot be guaranteed.*

Author contributions: *Sung Ho Jang (SHJ_a) and SSY designed this study, collected and analyzed data, and revised the paper. JPS and SHJ_a participated in study design and data collection. Sang Hyun Jin (SHJ_b), SHL and SSY participated in data collection and analysis and wrote the paper. All authors approved the final version of this paper.*

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