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Relation between NIRS signal and motor capability

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Abstract— **Brain activities of three subjects performing a right-hand tapping task were measured by near-infrared spectroscopy (NIRS). In experiments, the hemoglobin concentration change in the subjects' brains while they learned a new movement was analyzed. The results of these tests show that the channels covering the left primary motor cortex recorded a decreasing tendency in oxyHb when the subjects were repeating the tapping task. In contrast, the channels covering the supplementary motor cortex recorded an increasing tendency of oxyHb. Thease results suggest that the functional load on the brain decreases and the brain's active domain changes during motor learning.**

I. INTRODUCTION

Humans can improve the kinematic performance associated with a new movement (such as multi-finger tapping) by motor learning, even if they are not accustomed to the movement. The activation domain in the brain changes according to the stage of the motor learning. In the previous imaging study about the motor learning or the human cognitive function, an increase in the blood flow in the cerebellum was observed in the early phase of learning a new movement or a recognition task [1][2]. Additionally, a decrease in the local blood flow was observed on completion of the learning task [3]. Using functional Magnetic Resonance Imaging (fMRI), Toda et al. reported a decrease in the area of active domains in the cerebellum and a decrease in the functional load on the cerebrum as a result of motor learning [4]. However, because subject was instructed to perform the task performed in their study in a lying position, the movement performed in the experiment using fMRI was limited. Accordingly, fMRI is not suitable for motor-learning tasks that require postural control. On the other hand, Near-Infrared Spectroscopy (NIRS) makes it possible to measure cortical activations during dynamic movements such as walking and running. In fact, an experiment with NIRS makes it possible to investigate motor learning in an environment similar to an actual motor-learning environment [5][6].

The purpose of this study is to measure the NIRS signal when subjects perform a new movement and to investigate the relationship between the NIRS signal and motor learning. A multi-finger tapping movement was selected as the new-movement task.

II. EXPERIMENTAL METHODS

A. Subjects

Three healthy, right-handed subjects participated in the study (all subjects were 20 years old). Written informed consent was obtained from each subject. No subject had previous experience of the task to be investigated.

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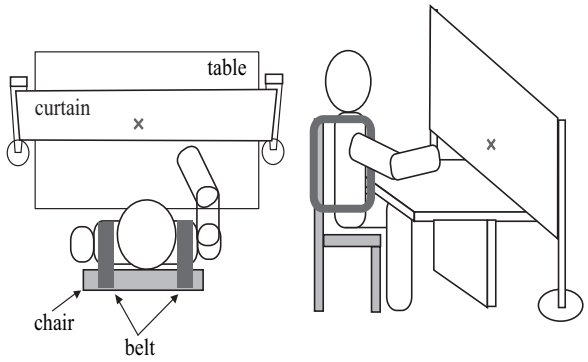

Fig. 1. Experimental set up

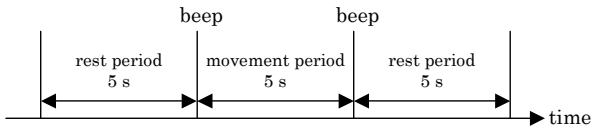

Fig. 2. Time sequence in task 1

B. Experimental environment

Figure 1 shows the experimental environment. Subjects sat in a chair with their body fixed by a belt. Their right hand was placed on the desk and their left hand on their thigh. A sign, about 10 cm in height and width, was marked on a white curtain.

C. Experimental task 1

The relationship between the NIRS signal and finger-muscle strength was determined before the tapping-task test for motor learning was performed. During the movement period of task 1, the subjects were instructed to pinch their thumb with another finger (middle or ring) of their right hand and to close their eyes. While resting, the subjects were instructed to gaze at the sign and relax.

Figure 2 shows the time sequence for task 1. One trial lasts 15 seconds (5 s: rest; 5 s: action; 5 s: rest). Each subject performed 20 trials. The time for the NIRS signal to stabilize before the next trial started was about one minute. The subjects were instructed to increase the strength of their finger after every five trial. The subjects were informed of the start and end of the movement periods by a beep.

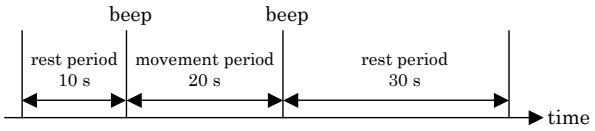

Fig. 3. Time sequence in task 2

D. Experimental task 2

The movement in task 2 was tapping of the right hand. Subjects were instructed to do the tapping task in time with an electronic metronome with a frequency of 3.00-3.17 Hz. The multi-finger tapping task is a movement of the fingers by which the thumb "taps" each of the other fingers in turn. While resting, they were instructed to gaze at the sign and relax. While moving, they were instructed to close their eyes. Figure 3 shows the procedure for each trial. Each trial takes 60 seconds (10 s: rest; 20 s: action; 30 s: rest). Each subject performed 12 or 15 trials. The time for the NIRS signal to stabilize before the next trial started was about one minute. The subjects were informed of the start and end of the movement periods by a beep.

E. Measurement instrument

The NIRS system used in the trials (an OMM-3000 from Shimadzu Corporation, Japan) consisted of eight near-infrared light-source probes and eight detectors, resulting in 24 source-detector pairs. A schematic illustration of the probe placement is shown in Fig. 4. The probes covered an area from the left primary motor cortex to the supplementary motor cortex (positioned according to the international 10/20 system for electrode placement). The sampling rate was 1/0.13 Hz. A CyberGlove (Virtual Technologies, U.S.A), put on the subject's right hand, measured tapping frequency. To determine the motor activity associated with the tapping task, electromyograms (EMGs) of the upper extremity were recorded during the task. Specifically, the EMGs were recorded from the flexor digitorum superficialis, brachioradialis, and extensor carpi radialis longus in the right upper extremity. Each EMG was recorded at 2000 Hz by a data acquisition unit (ODAU II, Northern Digital Inc., Canada) after it had been amplified by a multi-channel biological amplifier (MME-3132, Nihon Kohden, Tokyo).

III. Data analysis

A. Data preparation

During the trials, three kinds of concentration changes oxyHb, deoxyHb and totalHb, were measured. NIRS data was filtered by a low-pass filter with a cutoff frequency 0.5 Hz because a lot of high-frequency noises were included in the data. The mean value of all data recorded in the rest period (0-10 s) of each trial was taken as the base line and subtracted from the original signal.

B. Experimental task 1

Figure 5 shows the first trial data (EMG and hemoglobin concentration changes) of subject Y.M. Because the EMG signal is not steady at the beginning of the tapping movement, the mean EMG value between the 7 and 9 s time points was calculated. Similarly, the NIRS signal has a time lag of about three seconds from the start of the actual tapping movement, so the mean NIRS value between 10 and 12 s was calculated.

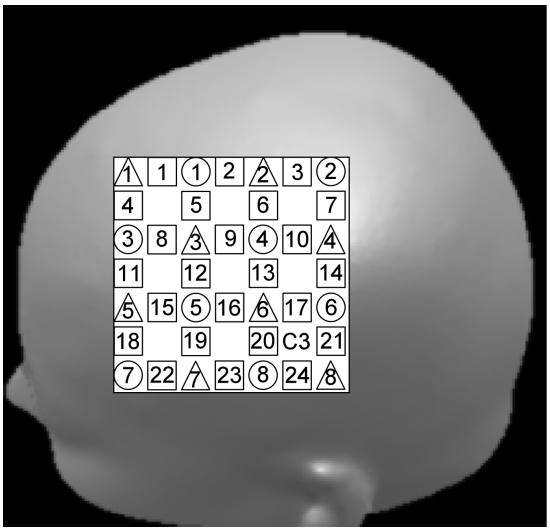

Fig. 4. Location of optodes.

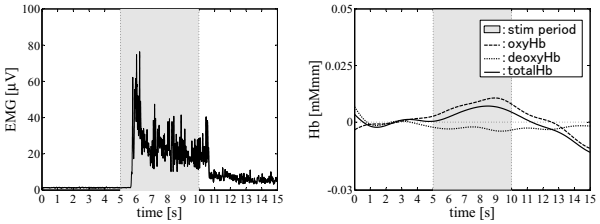

Fig. 5. The first trial data of subject Y.M in task 1

C. Experimental task 2

Figure 6 shows sixth-trial data (EMG and hemoglobin concentration changes) of subject Y.K doing task 2. As for task 1, the mean EMG value for task 2 was calculated from the data between the 10 and 27 s time points, and the mean NIRS value was calculated from the data between 13 and 30 s.

Table I lists the average number of taps (hereafter referred to as "tapping frequency") for each trial done by the three

TABLE I
NUMBER OF TAPS

subject	average	standard deviation
N.S	64.08	1.04
Y.M	59.40	1.85
Y.K	60.67	0.47

TABLE II

CORRELATION BETWEEN HEMOGLOBIN CONCENTRATION CHANGES AND TRIALS FOR TASK 2

Subject		Channel 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
N.S	Oxy	▼	▼	▼	▼	▼	▼	△	▼	▼	▼	▼	▼	▼	△	▼	▼	▼	△	▼	△	▼	▼	▼	▼
	deOxy	△	△	△	△	▼	▼	▼	△	△	▼	▼	△	▼	▼	▼	▼	△	▼	▼	▼	△	▼	▼	▼
	Total	△	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	△	▼	▼	▼	▼	▼	▼	▼
Y.M	Oxy	△	△	△	▼	▼	△	△	▼	△	△	▼	▼	△	▼	△	△	▼	▼*	▼	▼	▼	▼	▼	▼
	deOxy	▼	△	▼	△	△	▼*	▼	△	△	▼	△	△*	▼	△	△	▼	△	△*	△	△	▼	△*	△	△
	Total	△	△	△	△	▼	△	▼	▼	△	▼	▼	▼	▼	▼	△	▼	▼	▼	△	▼	▼	▼	▼	△
Y.K	Oxy	△	△	△	△	△	△	△	△	△	△	▼	▼	▼	△	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
	deOxy	▼*	△	△	▼	▼	△	▼	▼	▼	▼	△*	△	△	△	△*	△	△	△*	△	△	△	△	△*	△
	Total	△	△	△	△	△	△	△	△	△	△	△	▼	△	△	△	▼	▼	△	▼	▼	▼	▼	▼	▼

△: **Positive correlation** ▼: **Negative correlation** ∗: p<**0.05**

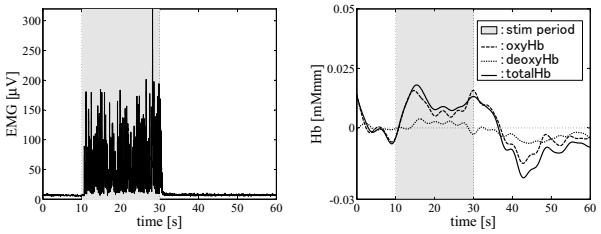

Fig. 6. Sixth-trial data of subject Y.K doing task 2

subjects. According to the table, the tapping frequency of the three subjects was almost constant. In addition, the mean value of EMG in each trial decreases as the number of the task cycles increases. Results of t-tests show a statistically significant decrease ($p < 0.05$) in the mean EMG values between the first half of trials and the latter half. Motor learning probably caused a statistically significant decrease in the mean EMG values between the first half of trials and the latter half. In the early phase of this experiment, movements of subjects' finger are inefficient because the subjects are not accustomed to the task. However, it is considered that the mean EMG values decrease because the subject becomes accustomed to the task as it is repeated.

Table II lists the correlations (i.e., positive or negative) between hemoglobin concentration change and trial number. The symbol △ shows that the channel exhibit a positive correlation between hemoglobin concentration and number of trials. Similarly, the symbol ▼ shows that the channel exhibit a negative correlation between hemoglobin concentration and number of trials. The symbol ∗ depicts a significant correlation in the uncorrelated test. Regarding the results of channels 18 to 24 ch that correspond to the left primary cortex, oxyHb decrease for all subjects. Also, regarding the results of channels 1 to 3 ch that correspond to the supplementary motor cortex, oxyHb increase for two subjects. The decreasing tendency of the three subjects' oxyHb was probably caused in response to the brain functional load decreased by the task trials. In addition, these results suggest that brain active domain associated with the motion planning may shift according to the learning process.

D. Relation of NIRS signal and EMG

In regards to task 2, the oxyHb measured on the channels covering the left primary motor cortex of the three subjects decreases as the tapping task is repeated. However, because the EMG signal strength decrease similarly to the NIRS signal strength, the decrease in NIRS signal strength may be due to changes in muscle strength. Thus, the mean values of EMG signal strength for tasks 1 and 2 were compared.

Figure 7 shows the EMG and oxyHb recorded on channel 23 for subject Y.K. The horizontal axis indicates the mean values of EMG for tasks 1 and 2, the vertical axis indicates hemoglobin concentration change, and the regression line was obtained by the least-squares method. Figure 8 plots the slope of the regression line for each channel. The slope is assumed to represent the correlation between hemoglobin density and EMG signal strength. According to the figure, overall, the slope in regards to task 1 is small, but the slope regarding task 2 is steeper for the channels covering the left primary motor cortex. That is, it is considered that the changes of NIRS signal (as described in section II.C) were not induced by muscle activities.

Figure 9 plots the mean values and standard deviation of EMG values for tasks 1 and 2. In each channel, the measurement region of EMG is shown. The figure shows that the difference between EMG values for task 1 and task 2 from each measurement region is small. It can thus be said that there is no significant difference in muscular power needed for task 1 and task 2.

IV. DISCUSSION

The results of two experiments involving repetition of a multi-finger tapping task by subjects show that oxyHb measured on channels covering the left primary motor cortex tends to decrease while oxyHb measured on channels covering the supplementary motor cortex tends to increase. In regards to task 1 (pinch subject's thumb with another finger) and task 2 (thumb "taps" each of the other fingers in turn), a difference between the slopes of the regression lines for the mean values of EMG and for oxyHb was confirmed, in spite that there was no difference in EMG values. This result is probably explained by the fact that the decrease in oxyHb is

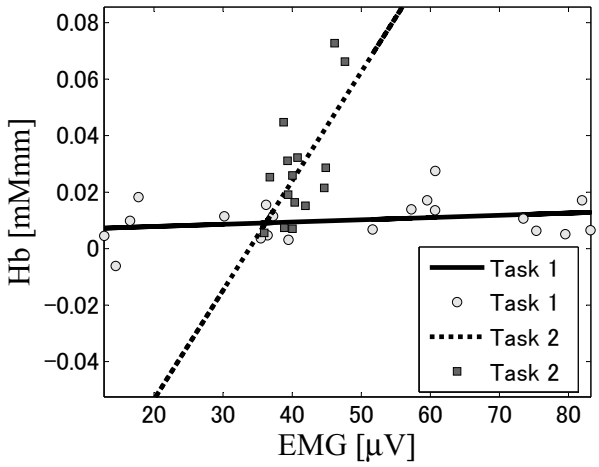

Fig. 7. Regression line of subject Y.K for channel 23

not related to EMG during the tapping task but to another factor. Accordingly, it is considered that the functional load on the brain decreases and the brain's active domain changes as the subjects learn the new movement (tapping task) by repeating it.

V. SUMMARY

To analyze the hemoglobin (oxyHb) in the human brain when subjects learn a new movement, the brain activities of three subjects during the right-hand tapping task were measured by near-infrared spectroscopy (NIRS). The NIRS results show that oxyHb measured on the channels covering the left primary motor cortex tend to decrease while oxyHb measured on the channels covering the supplementary motor cortex tends to increase. That is, the functional load on the brain (measured by channels covering the left primary motor cortex) decreases while the brain's active domain (monitored by channels covering the supplementary motor cortex) changes as a new movement is learned through repetition.

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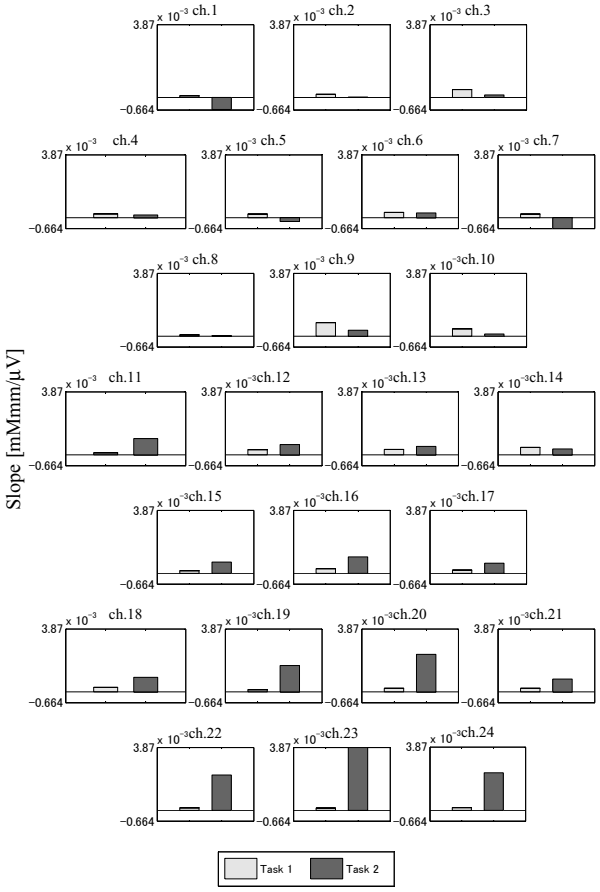

Fig. 8. Slope of regression line for each channel

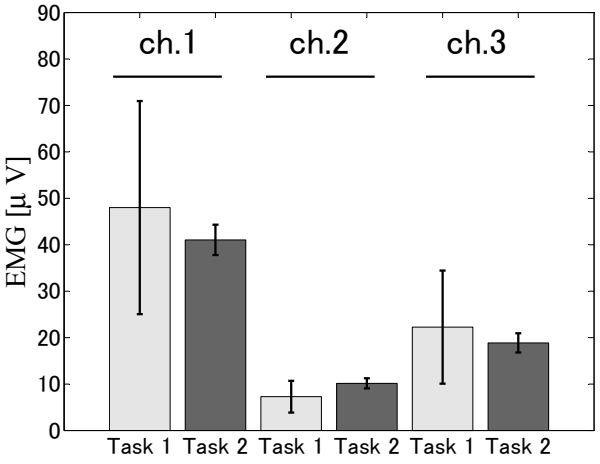

Fig. 9. Range of EMG