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Original Article

Comparing Brain Regions Involved in Axial and Limb Muscle Contraction

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Abstract : [Purpose] Previous studies have not compared brain activity during voluntary axial muscle contraction with that during voluntary limb muscle contraction. This study aimed to investigate differences in brain activation patterns during voluntary contraction of the axial and lower limb muscles. [Subjects and Methods] Three tasks were performed by 20 healthy male participants (24.2 ± 3.7 years): voluntary axial muscle contraction task; voluntary lower limb muscle contraction task; and an upright sitting task which required no voluntary contraction. Brain activity was measured in the motor-related regions, in addition, muscle activity was also measured in the axial and limb muscles. Comparisons of brain activity between tasks were conducted. [Results] Significant interactions were found for SMA and M1 brain activities. The SMA activated in the voluntary axial muscle contraction task than in the other tasks. Contrastingly, M1 activated in both the axial and lower limb muscle voluntary contraction tasks. [Conclusion] In conclusion, the SMA was specifically involved in voluntary axial muscle contraction, while M1 was involved in both voluntary contraction of the axial and lower limb muscles.

Keywords: axial muscle, lower limb muscle, brain activity

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I. INTRODUCTION

The axial and limb muscles play different roles during physical activity. Axial muscles stabilize the body axis during physical activity, while limb muscles enable elaborate movements such as object manipulation and ankle joint movement during walking [1, 2)]. Previous studies have reported that the innervation of the axial and limb muscles is different; for example, an animal study showed that the corticospinal tract innervates limb muscles while the cortico-reticular tract innervates the axial muscles [2)]. Furthermore, recent studies using diffusion tensor imaging in humans have reported that the primary motor cortex (M1) is the origin of the corticospinal tract and that the premotor cortex and the supplementary motor area (SMA) is the origin of the cortico-reticular tract [3)]. Therefore, it can be inferred that M1 is involved in limb muscle activity while the SMA is involved in axial muscle activity. In fact, previous studies examining the relationship between muscle and brain activities using transcranial magnetic stimulation (TMS) have shown that stimulation of both the SMA and M1 elicited the contraction of axial muscles [4)], while stimulation of only M1 elicited limb muscle contraction [5)].

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As mentioned above, previous studies have investigated the relationship between muscle and brain activity by using muscle contraction evoked by TMS. However, many motor dysfunctions seen in clinical practice are those of voluntary muscle contraction, represented by motor paralysis. In addition, to the best of our knowledge, the difference in innervation between voluntary muscle contraction in the axial and limb muscles is unclear. We believe that investigating differences in patterns of brain region activation between voluntary axial and limb muscle contraction, rather than during device-induced contraction, will facilitate understanding of the neurophysiological mechanisms of clinically relevant motor dysfunctions. Therefore, this study aimed to investigate differences in brain region activation patterns during voluntary axial and lower limb muscle contraction. We hypothesized that even during voluntary movements, there would be similar brain activity during involuntary contractions, as shown in previous studies, that is, increased SMA activity during axial muscle activity and increased M1 activity during limb muscle activity.

II. PARTICIPANTS AND METHODS

1. Participants

This study included 20 healthy males (mean [± standard deviation] age 24.2 ± 3.7 years, height: 171.8 ± 5.5 cm, and weight: 63.5 ± 12.5 kg). The exclusion criteria were (1) signs of neurological disease and (2) previous surgical treatment of the spinal column or lower limb. All participants were informed of the experimental procedures and provided informed consent. This study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Research Safety and Ethics Committee of Arakawa Campus, Tokyo Metropolitan University (no. 18026).

2. Methods

Participants sat in a height-adjustable chair and performed three sets of three different tasks consisting of 15 s of pre-task rest, 15 s of task performance, and 15 s of post-task rest. As shown in Figure 1, participants performed an upright sitting task (UST), that only required participants to sit up straight; a trunk draw-in task (DRT) that required voluntary axial muscle contraction; and an ankle plantar flexion task (PFT) that required voluntary lower limb muscle contraction.

Each task was repeated thrice by each participant; and the order of the three tasks was randomly changed for each participant. The following instructions were given verbally for each task: the UST required only sitting upright posture; the DRT required drawing in the participant's abdomen in an upright sitting posture; and the PFT required maximum ankle joint plantar flexion in an upright sitting posture (Fig. 1). During rest periods, the participants were instructed to sit in a relaxed position with their knees flexed at 90°. During both the rest and task periods, participants were instructed to gaze at a fixed point 3 m in front of them.

A) B) C) D)

Fig. 1: Photographs of the three tasks and rest periods.
A) shows the upright sitting task (UST); B) shows the trunk draw-in task (DRT), and a red arrow indicates abdominal draw-in; C) shows the ankle plantar flexion task (PFT), and a red arrow indicates ankle plantar flexion; D) shows the posture adopted during the rest period.

Measurements of brain activity

Brain activity was measured using a functional near-infrared spectroscopy (fNIRS) system (FOIRE-3000; Shimadzu Corp., Kyoto, Japan). Near-infrared light passed through 40 channels consisting of 13 sending and 12 receiving fibers, and oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) values were measured in all channels according to the modified Lambert–Beer law. Since neuronal activity is typically assumed to be mirrored by an increase in oxy-Hb and a decrease in deoxy-Hb [6, 7], oxy-Hb and deoxy-Hb values were used as indicators of brain activity in this study. A whole-head holder was used, and the light source at the center point of the 5 × 5 matrix was positioned at the top of the head in accordance with the international 10-20 method. The distance between the optodes was 3 cm, and the sampling frequency was 23.8 Hz. The regions of interest (ROIs) were the prefrontal cortex (PFC), SMA, primary motor cortex (M1), and superior parietal lobule (SPL). Mapping between the measurement channels and Brodmann areas was performed using a 3D position measurement system (FASTRAK; Polhemus, Colchester, VT, USA), MATLAB (Matlab 2019b Mathworks, MA), and NIRS-SPM. Channels with a better than 80% fit to the ROI were adopted [8]. Accordingly, the left and right PFC were represented by ch5, 9; the SMA by ch16, 20, 21; M1 by ch25; and the left and right SPL by ch33, 35, 37, 40 (Fig. 2).

A band-pass filter with cut-off frequencies from 0.01 to 0.1 Hz was applied to the data in order to reduce very slow drifts and high frequency noise [9, 10]. Furthermore, principal component analysis (PCA) was performed, and components accounting for 80% of the total variance were removed to reduce physiological and motion artifacts [11]. After processing, the oxy-Hb and deoxy-Hb data were averaged across the three repetitions of each rest and task (Fig. 3).

Additionally, the effect sizes of each channel were calculated according to Cohen's d [12] to quantify the task-related changes in oxy-Hb and deoxy-Hb levels according to the formula below:

$$\text{Effct size(d)} = \frac{(m1-m2)}{\sqrt{\frac{S1^2-S2^2}{2}}}$$

Where m1 represents the mean oxy-Hb value during the tasks; m2 represents that of the rest conditions; and s1 and s2 are the standard deviations for the task and rest conditions, respectively. To calculate the effect sizes for each ROI, we first calculated the effect sizes for each channel in each task. Second, the values in each channel that constructed the ROIs were averaged.

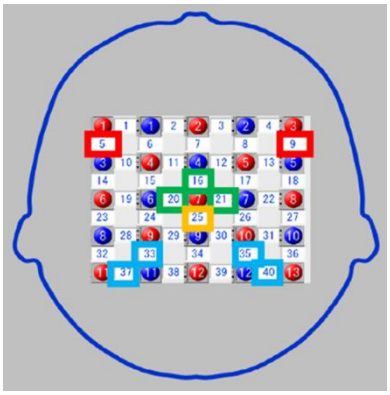

Fig. 2: placements of ROIs of fNIRS,
Red square: dorsolateral prefrontal cortex; green square: supplementary motor area; orange square: primary motor cortex; light blue square: superior temporal lobule.

Measurements of muscle activity

Muscle activity during the three tasks was measured bilaterally using a wireless surface electromyograph (EMG; WEB-7000, Nihon Kohden, Tokyo, Japan). The skin was wiped with abrasive and alcoholic cotton to reduce the electrical resistance. The target muscles were both sides of the internal oblique (IO; 2 cm

below and 2 cm medial to the anterior superior iliac spine), lumbar erector spinae (LES; 2 cm lateral to the third lumbar vertebra), and the medial head of gastrocnemius (GS; 2 cm medial to the midline and below the five finger distances from the posterior surface of the knee joint in the popliteal fossa) [13, 14]. Maximal voluntary activity (MVC) in each muscle was measured to standardize the muscle activity for 3 s after each practice movement. To measure the MVC of the IO, participants lay in a supine position and lifted one scapula from the bed, against manual resistance applied to the anterior surface of their shoulders. To measure the MVC of the LES, the participant was placed in a prone position and the investigator fixed their legs. Then, the participants placed their hands behind their heads and extended their trunk maximally, against manual resistance applied to the middle of both scapulae. To measure the MVC of the GS, the participants were placed in a supine position with their hands grasping both sides of the bed and plantarflexed maximally against manual resistance applied to the sole of the foot. The signal was sampled at 1000 Hz, bandpass filtered at 15-500 Hz and full wave rectified. In the measurement of MVC, we calculated the integrated value of an arbitrary 1 s in which the EMG signal was steady. To measure muscle activity during each task, we calculated the integrated value of the last 10 s of task execution and then averaged them (Fig. 3). The averaged integrated values of each task were normalized to that of the MVC, and then the bilateral activities of each target muscle were averaged.

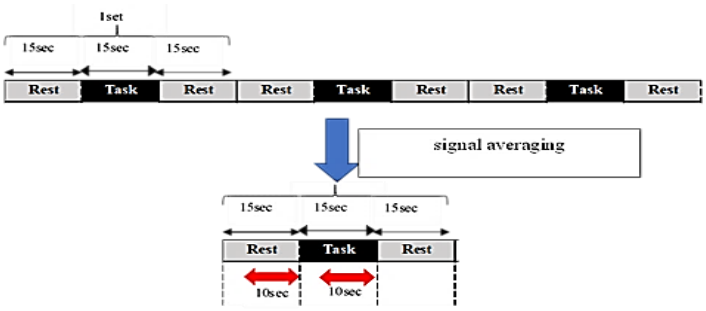

Fig. 3: Experimental protocol and ranges of analysis.
Each task was repeated for three sets; a single set consisted of 15 s of rest, 15 s of task, and 15 s of rest. We analyzed the last 10 s of rest and task in the averaged data (bidirectional arrows).

Statistical analysis

First, repeated-measures one-way analysis of variance (ANOVA) or Friedman's test was conducted to identify the difference in muscle activity between each task. Tukey's test or Wilcoxon's signed-rank test was used for multiple comparisons. In addition, a repeated measures two-way ANOVA with time (rest, task) and task type (UST, DRT, EXT) factors was conducted to compare the changes in brain activity between tasks. If an interaction was found, a simple main effect analysis was performed using repeated-measures one-way ANOVA or Friedman's test. R version 4.0.0 (R Foundation for Statistical Computing, Vienna, Austria) was used for the statistical analysis, and the significance level was set at 5%.

III. RESULTS

Our comparison of muscle activity during each task is shown in Table 1. In the DRT, which required voluntary axial muscle contraction, the IO showed significantly higher %MVC values than in other tasks (DRT vs. UST, $p = 0.001$; DRT vs. PFT, $p = 0.02$). Likewise, the LES showed significantly higher activity in the DRT than in the other tasks (DRT vs. UST, $p = 0.04$; DRT vs PFT, $p = 0.04$). In the PFT, which required voluntary limb muscle contraction, the GS showed significantly higher %MVC values than in all other tasks (PFT vs. DRT, $p = 0.03$; PFT vs. UST, $p = 0.001$) (Table 1).

A repeated-measures two-way ANOVA showed significant interactions between the SMA ($p = 0.01$) and M1 ($p = 0.003$) (Fig. 4). Moreover, a simple main effect analysis of task factors (UST, DRT, and PFT)

revealed significantly larger effect sizes for the SMA in DRT than those in the others (vs. PFT, p = 0.03; vs. UST, p = 0.0003). In addition, M1 showed significantly higher effect sizes in DRT and PFT than in UST (DRT vs. UST, p = 0.002; PFT vs. UST, p = 0.006) (Table 2). A simple main effect analysis of time factors (rest, task) revealed that oxy-Hb concentration in M1 significantly increased during DRT (p = 0.04) and significantly decreased during UST (p = 0.01) (Table 3).

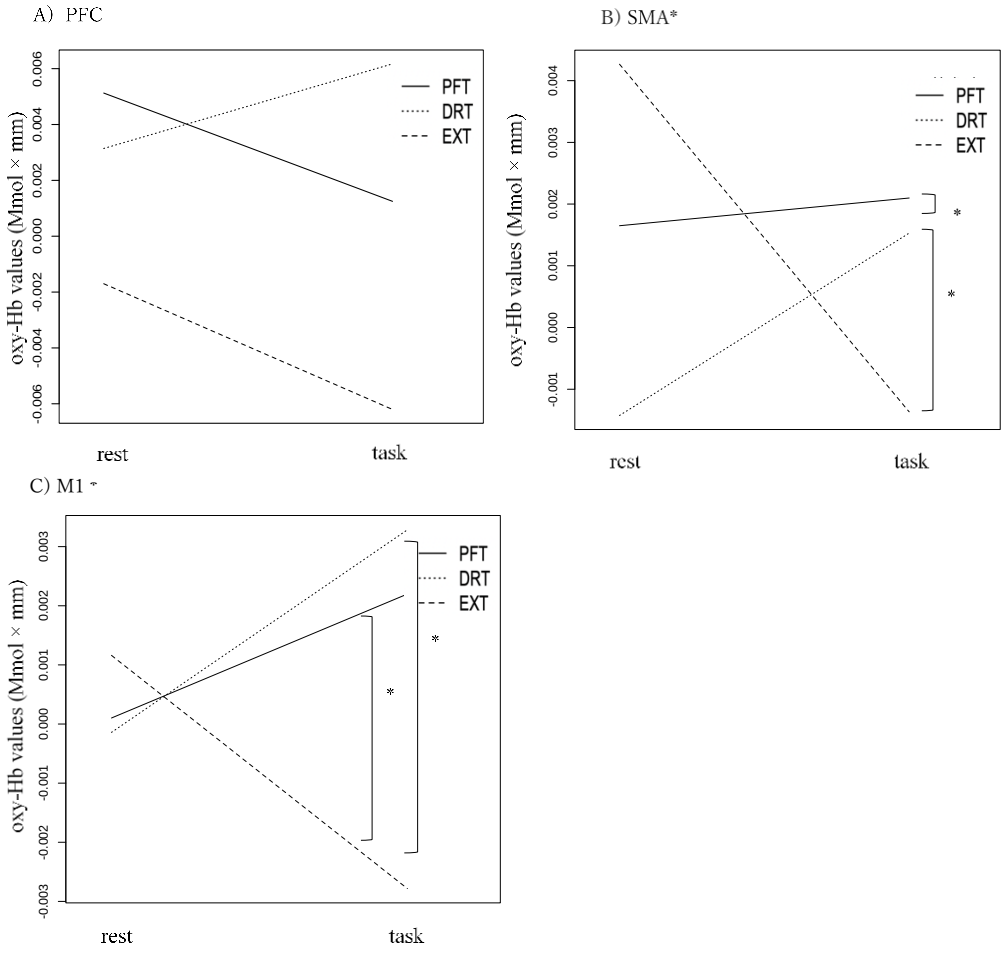

Fig. 4: Illustration of the interaction in oxy-Hb values by time and type of task.
Unit: Mmol × mm. *: significant interaction was shown (p < 0.05). A) PFC: Prefrontal cortex; B) SMA: Supplementary motor area; C) M1: Primary motor cortex. PFT: ankle plantar flexion task; DRT: trunk draw-in task; UST: upright sitting task. There was no significant difference in oxy-Hb values at resting state between tasks.

Table 1: Comparison of muscle activity during each task.

Muscle	UST	DRT	PFT	Points of Observation
IO	9.2 ± 5.4	41.1 ± 25.0	12.3 ± 5.7	a, b
LES	7.4 ± 2.5	11.1 ± 7.3	9.5 ± 4.5	a
GS	8.3 ± 4.4	8.6 ± 4.4	23.2 ± 15.4	c

Unit: %MVC. Average ± standard deviation of %MVC values for each task. Friedman tests were conducted for all variables. UST: upright sitting task; DRT: trunk draw-in task; PFT: ankle plantar flexion task. IO: internal oblique, LES: lumbar erector spinae, GS: gastrocnemius. a: %MVC of the DRT higher than that of the others ($p < 0.05$); b: %MVC of the PFT was higher than that of the UST ($p < 0.05$); c: %MVC of the PFT was higher than that of the others ($p < 0.05$).

Table 2: Comparison of the effect sizes of oxy-Hb values between each task.

Brain Region	UST	DRT	PFT	p-values
PFC	-1.38 ± 2.49 *	1.10 ± 2.52 *	-0.47 ± 1.79	0.003 *
SMA	-1.01 ± 1.14 *	1.10 ± 1.24 *	-0.19 ± 1.61	0.001 *
$M1^R$	-1.16 ± 1.81 *	0.97 ± 1.89 *	0.69 ± 2.03	0.001 R*
SPL	0.32 ± 2.44	0.95 ± 2.05	-0.32 ± 1.50	0.51

Mean ± standard deviation of the effect sizes of oxy-Hb. UST: upright sitting task, DRT: trunk draw-in task; PFT: ankle plantar flexion task. PFC: prefrontal cortex; SMA: supplementary motor area; M1: primary motor cortex; SPL: superior parietal lobule. R: Repeated-measures one-way analysis of variance was used for statistical testing. *: Significant difference between tasks.

IV. DISCUSSION

This study aimed to demonstrate the differences between patterns of brain region activation during voluntary contraction of the axial and limb muscles. The results showed that voluntary axial muscle contraction (DRT) was associated with increased SMA and M1 activity whereas voluntary lower limb muscle contraction (PFT) was only associated with increased M1 activity. This study suggests that even in voluntary contraction, different neural mechanisms exist between the axial and lower limb muscles.

In the repeated-measures two-way ANOVA, the brain activity of SMA showed a significant interaction in time and task type factors and a higher effect size in voluntary axial muscle contraction task (DRT); and the brain activity of M1 showed a significant interaction and higher effect size in both voluntary contraction of the axial and lower limb muscle tasks (Fig. 4, Table 2). These results suggest that the SMA is specifically activated during voluntary axial muscle contraction, whereas M1 is activated during voluntary contraction of both the axial and lower limb muscles. Our results are consistent with previous studies showing that TMS to the SMA can induce contraction of axial muscles [4, 15], and a study that revealed that pelvic floor muscle contraction activates the SMA [16, 17]. In addition, previous studies showing anatomical findings have reported that the SMA and premotor areas are the origin of the cortico-reticular tract [18, 19], which is thought to innervate the axial muscles. These findings suggest the existence of a direct pathway from the SMA to the axial muscles [15]. Therefore, in the present study, the background of the higher effect size observed in the SMA during voluntary axial muscle contraction task (DRT) may have involved the presence of neural pathways from the SMA to the axial muscles, such as the cortico-reticular pathway. The oxy-Hb values of M1 showed a significant interaction and higher effect size during both axial and lower limb muscle voluntary contraction compared with the UST, which did not require voluntary muscle contraction (Table 3, Fig. 4). The presence of a somatotopic arrangement in M1, known as the homunculus, has been demonstrated; and it is known that M1 is activated during voluntary contraction of axial and lower limb muscles [20, 21]. Consistent with previous studies, voluntary contraction of the axial and lower limb muscles was associated with M1 activation in the present study.

A comparison of brain activity at rest and during each task showed that only M1 was significantly activated in the DRT ($p = 0.04$), and no significant increase in oxy-Hb values during each task was observed in the PFC, SMA, and SPL (Table 3). As for why these brain regions showed no significant increase in brain activity during the tasks, previous studies have reported individual differences in brain regions [22] and low mental load for the tasks [23]. It is possible that the tasks in the present study required only local voluntary muscle contractions in the sitting position and therefore did not have sufficient mental load to induce significant increases in brain activity from rest to task. This was especially apparent in the UST, which did not require voluntary muscle contraction. In this task, muscle activity of the IO, LES, and GS was significantly lower than in the other tasks (Table 1), and brain actibity in the PFC, SMA, and M1 decreased from the rest condition (Fig. 4). The decrease in oxy-Hb values occasionally observed in fNIRS studies is caused by technical and physiological factors [23]. The decrease in oxy-Hb values due to technical factors (e.g., position of the transmitter and receiver probes relative to the region of interest) is accepted as occurring in one or two localized channels [23]. However, when a decrease in oxy-Hb values in all regions of interest is observed, as in the results of this study, physiological factors must be considered. As a physiological factor, tasks requiring only low mental and cognitive loads show lower oxy-Hb levels, that is, lower neural activity [24, 25]. The UST in this study was a task which did not require voluntary muscle contraction and reproduced a posture performed in activities of daily living. Therefore, in the UST, oxy-Hb levels were considered lower than those at rest.

This study has several limitations. First, because the number of participants was limited, the influence of individual differences in brain activity cannot be ruled out. Future studies with larger numbers of participants are needed. Second, systemic biological signals (e.g., blood pressure, pulse rate, and respiratory rate), which have been indicated to potentially influence fNIRS signals, were not measured [7]. Future studies should include the measurement of systemic biological signals. Third, the study did not include subjective measures, such as participants' perceived difficulty of the task. This may have led to

underestimation of individual differences in explaining the oxy-Hb values. In future studies, it would be desirable to measure not only biometric signals but also subjective scales. Finally, this study did not standardize the amount of load due to the task across subjects. In the future, it will be necessary to standardize the amount of loading to each subject by, for example, %MVC value, to minimize the effects of individual differences in the amount of loading from task to task.

In conclusion, this study revealed differences in brain activation regions during voluntary contraction of axial and lower limb muscles and provided the basic data of motor paralysis in clinical practice; the possible involvement of SMA in axial motor paralysis and M1 in both axial and limb motor paralysis. Further study is needed to determine whether top-down interventions to activate SMA and M1 affect trunk and limb motor function.

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FUNDING AND CONFLICT OF INTEREST

This study was conducted without grants or funding.

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