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Original Article

Contribution of the dorsolateral prefrontal cortex activation, ankle muscle activities, and coactivation during dual-tasks to postural steadiness: a pilot study

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Abstract. [Purpose] To examine the influence of dorsolateral prefrontal cortex (DLPFC) activation, ankle muscle activities, and coactivation on postural steadiness during dual-tasks. [Participants and Methods] A total of 14 participants (8 males, 6 females) were included. The participants stood straight on the force plate, and performed 3 different tasks: 1) a quiet standing (single-task), 2) a repetition of a number (dual-task 1: DT1), and 3) a serial subtraction (dual-task 2: DT2). We divided the participants into 2 groups (S and L group) according to whether their center of pressure paths in the dual-tasks were shorter or longer than those in the single-task. The EMG activity of the gastrocnemius lateralis and tibialis anterior were measured; the oxygenated hemoglobin (oxy-Hb) level in the DLPFC were measured using fNIRS. [Results] The results revealed that oxy-Hb in the left DLPFC increased significantly in all participants during DT2 compared to a single-task. Further, we found that the S group exhibited a higher rate of tibialis anterior activity and ankle muscle coactivation than the L group during DT2. [Conclusion] We concluded that the increase of the DLPFC activation varied with the dual-tasks; moreover, younger individuals modulate their standing posture using different strategies for posture steadiness during posture-calculating task.
Key words: Dorsolateral prefrontal cortex, Ankle muscle activities, Postural steadiness

INTRODUCTION

Human postural control is continuously and automatically maintained. However, recent research has suggested that postural stability is a complex process requiring coordination between sensory input, cognitive processing, and motor control[1, 2]. In addition, there are significant attention requirements for postural control. Dual-task interference, in which postural task and a secondary cognitive task are performed at the same time, results from the sharing of a limited capacity for information processing[1]. However, the regulation mechanism of dual-task interference in posture control is not clear. In upright standing there is diversity of views on dual-task effects because healthy subjects can have both, increased and decreased postural sways under dual-task conditions[3–5]. It is suggested from psychology that attention requirements on postural control vary depending on whether sharing of a limited amount of attention processing or a competing order of priority between tasks is occurring in the brain[1].

The prefrontal cortex (PFC) is hypothesized to integrate sensory information and select the appropriate motor responses according to various circumstances in maintaining balance. In particularly, the dorsolateral PFC (DLPFC) is associated with an attention controller, that allocates and coordinates attention resources during dual-task performances. Prefrontal neural activation should be an important factor in the postural control mechanism of dual-task interference. One possible noninvasive method for investigating prefrontal neural activation during physical condition is to use near-infrared spectroscopy (fNIRS), and there have been a few studies on cortical activation while maintaining balance and performing another accompanying task, using fNIRS. Fujita et al.[6] reported that young participants, who achieved a high score on cognitive tasks, showed an increase of oxygenated hemoglobin (oxy-Hb) in DLPFC and less postural sway, as compared with those who scored low, while performing a dual-task on one standing leg. The author suggested that only the participants in the high-score group were able to allocate resources to both, the cognitive task and posture balance and that different working memory capacities may result in different brain activation influencing a motor task. A study[7] using a dual-task paradigm found increases in oxy-Hb in the DLPFC when the difficulty of a postural task was increased. There were no changes when a cognitive load was added to standing, suggesting that performing a dual-task was influenced more strongly by postural than cognitive loads. These studies indicate that the DLPFC activation devoted to postural control are dependent on the difficulties of the standing posture and working memory capacities. However, none of the studies assessed the relationship between DLPFC activation and ankle muscle activities with postural steadiness during dual-task performances, which are an essential feature in maintaining balance during dual-task performances.

Therefore, the purpose of this study was to investigate how the DLPFC, ankle muscle activation and muscle coactivation contribute to postural steadiness during dual-task performances. We hypothesized that the DLPFC activation would be larger during dual-task performance compared with single-task. In addition, we further hypothesized that the postural steadiness during dual-task performance would characterize the effects of relationship between the DLPFC activation and ankle muscle activation.

Postural balance coping-with-attention requirements are susceptible to aging, and there are concerns about an increased risk of falling in older adults. The results in this study may be important for aging effects on the DLPFC activation and postural steadiness, including ankle stiffness during dual-task performance.

PARTICIPANTS AND METHODS

The participants were 14 healthy volunteers consisting of 8 males and 6 females (age, 20.7 ± 1.5 years; height, 165.6 ± 8 cm; weight, 57.6 ± 14.5 kg). They had no medical history of neurological or orthopedic disorders or injuries. Ethical approval for the study was granted by the Osaka Yukioka College of Health Science (0002), and informed consent was obtained from all participants.

The participants performed three types of tasks while standing upright on a force platform (model K40, Patela Inc., Tokyo, Japan): standing still (single-task); repeating a number, 101 (dual-task 1, DT1); and subtracting 7 beginning from one of the following numbers: 598, 599, 601, 602, 603, or 604: while standing (dual-task 2, DT2) until the session timed out. The results of each task were spoken out loud so that the accuracy could be assessed. While repeating a number (DT1), we needed to ensure that the effect of a prompt prefrontal neural activity, merely by counting numbers aloud, was minimal. Each participant stood and relaxed, waiting for the task instruction. After hearing "go," they randomly performed each task for 30 seconds along with the cue, and took a minute's rest between tasks. They repeated this sequence 3 times until the remaining tasks were done. To reduce artifacts from waveforms on the platform, the participants were instructed to stand still and stare at a letter "X", which was displayed 2 m away.

We focused on the analysis of the center of pressure (COP) displacements in the anteroposterior and mediolateral directions and converted these into trajectory lengths by the following formula:

$$\sum_{t=0}^{10} \sqrt{(a_2 - a_1)^2 + (b_2 - b_1)^2}$$

during an observation window of 10 seconds, just before the completion of each task. To compare between decreased and increased postural steadiness, we divided the participants into two groups based on the trajectory length in the single-task; 6 participants had shorter (S group) and 6 participants had longer (L group) trajectory length in both, DT1 and DT2 compared to the corresponding single-task. Two participants were excluded because they did not exhibit the expected similar increase or decrease in their postural sway between DT1 and DT2, as compared to the single-task.

We used fNIRS (OEG-16, Spectratech Inc., Tokyo, Japan) for measuring the left and right DLPFC activation in this study. The 12 NIRS probes (6 near-IR light sources and 6 detectors, channels 1–16) were fixed on the forehead at a distance of 3 cm. Changes were monitored in the concentrations of oxy-Hb and deoxygenated hemoglobin (deoxy-Hb) in the left (channels 14–16) and right DLPFC (channels 1–3) using near-IR wavelengths (770 nm and 840 nm) with sampling every 650 ms. In our study, only the changes in oxy-Hb values were used for analyzing the changes in prefrontal cerebral blood volume, since oxy-Hb is a more sensitive parameter than deoxy-Hb for measuring blood flow changes associated with brain activation[8]. We defined DLPFC activation by the increase in oxy-Hb over the oxy-Hb level detected at the initiation of each task. We
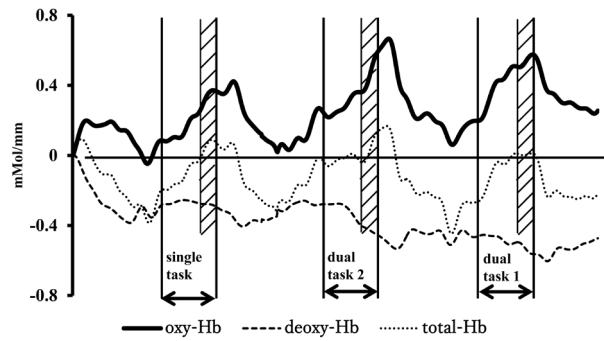
Fig. 1. Changes in concentrations of oxyhemoglobin (oxy-Hb), deoxyhemoglobin (deoxy-Hb), and total hemoglobin (total-Hb) from a representative channel (CH 15). The vertical line shows the relative amount and the horizontal one the clock time. The baselines were selected from the beginning of each task, and the changes from the baseline were presented as relative amounts. The changes of oxy-Hb analyzed were taken from the observation window of 10 seconds just before the completion of each task (shaded area). The figure was an example of a 22-years-old male participant. In this case, a single-task came the first for 30 seconds and continued to the dual-task 2 and dual-task 1. There was a minute intermission among tasks.

performed baseline correction and analyzed the time integration value in the change of oxy-Hb in the observation window of 10 seconds just before the completion of each task (Fig. 1).

We also measured tibialis anterior (TA) and gastrocnemius lateralis (GL) muscle activities using surface electromyography (EMG). We obtained the root-mean-square (RMS) of direct EMG data using analysis software (Flex Pro Ver. 7, Weisang GmbH, St. Ingbert, Germany) and analyzed the RMS in an observation window of 10 seconds just before the completion of each task. Muscle coactivation was calculated by the coactivation index (CI) and expressed as percent activation[9] by the following formula:

$$CI = 2 \times \frac{RMS[EMG_{TA}]}{RMS[EMG_{TA} + EMG_{GL}]} \times 100$$

Compared to the S group and L group, the sway path length, the RMS of the EMG data for the TA, GL, and muscle coactivation in DT1 or DT2 were renormalized as a percentage of those in the single-task. The oxy-Hb level in the left and the right DLPFC were standardized by subtracting the oxy-Hb value of the single-task from DT1 or DT2. During the experiment, the trajectory lengths and the data of EMG activities in the TA and GL were recorded in synchronization with a computer at 200 Hz.

One-way analysis of variance (ANOVA) was used to detect significant differences in the sway path lengths, the oxy-Hb levels, RMS of the EMG data, and muscle coactivation between the single-task, DT1, and DT2. The oxy-Hb level, the RMS of the EMG data, and muscle coactivation between the S and L group of DT1 and DT2 were compared using two-way ANOVA. When a one-way or two-way ANOVA was found to be significant, the Tukey post hoc test was used for multiple comparisons. The level of statistical significance was set at $p < 0.05$.

RESULTS

Table 1 shows the postural sway, oxy-Hb levels, ankle muscle activity, and muscle coactivation compared between task factors. In the postural sway, ankle muscle activity, and muscle coactivation, one-way ANOVA revealed no significant difference between task factors. However, there was a significant difference of oxy-Hb levels in the left DLPFC between task factors ($F=5.913$, $p=0.013$). Post hoc tests revealed a significant difference in oxy-Hb levels in the left DLPFC between the single-task and DT2 ($p=0.011$).

Table 2 shows the % postural sway, oxy-Hb levels, % ankle muscle activity, and % muscle coactivation during dual-tasks compared with single-task.

Table 1. Comparison of postural sway, brain activation and muscle activity between tasks

	Single-task	DT1	DT2
Sway path length (cm)	12.8 ± 4.68	12.3 ± 4.53	12.8 ± 5.01
Oxy-Hb (mMol·mm)			
DLPFC right	0.53 ± 0.51	0.90 ± 0.88	1.09 ± 1.04
DLPFC left[a]	0.47 ± 0.54	0.82 ± 0.54	1.13 ± 0.75*
Muscle activity (mV)			
Tibialis anterior	0.17 ± 0.09	0.16 ± 0.09	0.15 ± 0.09
Gastrocnemius lateralis	0.12 ± 0.06	0.11 ± 0.04	0.11 ± 0.04
Coactivation (%)	116 ± 24	115 ± 23	113 ± 23

Value are mean ± SD.

Single-task: standing still, DT1: repeating a number during standing, DT2: calculating during standing.

[a]DT2 increased the value in oxy-Hb significantly compared to the single-task.

*$p < 0.05$.

Table 2. Comparison of postural sway, brain activation and muscle activity in shorter and longer groups

	DT1		DT2	
	Shorter group	Longer group	Shorter group	Longer group
Sway path length (%)[a]	85.0 ± 10.6	109.0 ± 6.13*	89.7 ± 10.5	107.0 ± 3.69*
Oxy-Hb (mMol·mm)				
DLPFC right	0.50 ± 0.68	1.27 ± 0.41	0.84 ± 0.94	1.38 ± 0.25
DLPFC left	0.14 ± 0.31	0.54 ± 0.65	0.56 ± 0.40	0.82 ± 0.47
Muscle activity (%)				
Tibialis anterior[b]	99.8 ± 1.44	89.6 ± 11.8	102.0 ± 1.85	84.0 ± 17.8*
Gastrocnemius lateralis	99.3 ± 4.31	96.2 ± 14.2	98.5 ± 2.60	96.8 ± 17.5
Coactivation (%)[b]	100.3 ± 2.50	96.6 ± 5.38	102 ± 1.98	92.6 ± 7.82*

Value are mean ± SD. DT1: repeating a number during standing, DT2: calculating during standing.

[a]There were no significant differences between DT1 and DT2; however, significant differences were observed between the groups with both tasks.

[b]There were no significant differences between DT1 and DT2; however, significant differences were observed between the groups in DT2.

*$p < 0.05$.

A two-way repeated measure ANOVA revealed no significant differences in the % postural sway between tasks [$F_{(1, 20)}=0.11$, $p > 0.05$]. Statistically significant differences were observed between the groups within both tasks [$F_{(1, 20)}=36.5$, $p < 0.01$]. Furthermore, there were no significant interactions between the tasks with regard to the groups [$F_{(1, 20)}=1.08$, $p > 0.05$]. After applying a post hoc tests to these results, the % postural sway was significantly larger in the longer groups of DT1 ($p < 0.001$) and DT2 ($p < 0.05$) compared with the shorter groups. A two-way repeated measures ANOVA revealed no significant differences in the % muscle activity of the TA between tasks [$F_{(1,20)}=0.18$, $p > 0.05$]. Statistically significant differences were observed between the groups in DT2 [$F_{(1, 20)}=9.96$, $p < 0.01$]. Furthermore, there were no significant interactions between the tasks with regard to the groups [$F_{(1, 20)}=0.72$, $p > 0.05$]. After applying a post hoc tests to these results, the % muscle activity of the TA was significantly larger in the shorter group of DT2 ($p < 0.05$) compared with the longer group. A two-way repeated measures ANOVA revealed no significant differences in the % muscle coactivation between the groups [$F_{(1,20)}=0.42$, $p > 0.05$]. Statistically significant differences were observed between the groups in DT2 [$F_{(1, 20)}=9.53$, $p < 0.01$]. Furthermore, there were no significant interactions between the tasks with regard to the groups [$F_{(1, 20)}=1.68$, $p > 0.05$]. After applying a post hoc tests to these results, the % muscle coactivation was significantly larger in the shorter group of DT2 ($p < 0.05$) compared with the longer group.

In addition, the results of present study show there was no significant difference in the accuracy of calculation between the groups.

DISCUSSION

Our results from this study revealed that the oxy-Hb levels of the left DLPFC significantly increased when participants stood while calculating. According to a previous study, the more the brain is active, the higher the level of oxygen and glucose in the blood supplied to the brain; these are necessary for metabolism at the cellular level[8]. In fact, it was reported that the left DLPFC, parts of which are concerned with verbal working memory and calculation performance[10, 11], displayed increased activation during DT2. Previous studies also indicated that the regions active in the PFC during performance of

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cognitive tasks revealed an age-related difference. Cabeza et al.[12] reported that older adults showed bilateral activations in the DLPFC, what is called "compensatory reallocation", when they perform demanding cognitive tasks compared to circumscribed and unilateral activation in young adults. Furthermore, Hyodo et al.[13] reported that acute moderate exercise improved the activation of the right DLPFC in older adults; this was associated with contralateral compensation activation. In addition, the oxy-Hb levels in DT1 in this study showed no significant difference compared to a single-task. Although the tasks of both DT1 and DT2 included the contents being spoken out loud to assess verbal accuracy, it was observed that there was little effect from the prompt prefrontal neural activation by just standing, speaking, and repeating numbers.

Meanwhile, there were no significant differences of postural sway between the tasks. In general, normal static standing is performed automatically, requiring few attentional resources for controlling balance. However, Shumway-Cook and Woollacott[1] reported that postural control during the performance of another attention-demanding task results from the sharing of limited amount of the attention resources or the competing order of priority between postural tasks and cognitive or motor tasks occurring in the brain. Especially in older adults with balance impairment and adults with neurologic impairment, the attention demands associated with postural control appear to be different from healthy young or old adults. This is known as a posture-first strategy, and attention resource allocation are prioritized to maintain a static standing posture even on a flat floor[14]. Our results indicate that younger participants prioritized attention resource allocation to calculating tasks during posture dual-task, since the level of postural performance should not have a detrimental effect on postural control for them.

As mentioned before, no studies have demonstrated why an increase or decrease of postural sway in postural stability occurs in the dual-task condition. In our study, we divided participants into S and L groups and there were significant increases in the ratio of TA muscle activation and coactivaction in the S group compared to L group in DT2. Since the COP variability is approximately proportional to ankle joint torque variability[15], our results showed that the younger participants exhibited a variety of ankle muscle coordination patterns to stabilize posture during posture-calculating dual-task. Activity of the distal ankle muscles, such as the GL, soleus (SOL), and TA, are required for reestablishing stability in response to anterioposterior instability. This is called the "ankle strategy," the primary mechanism of controlling upright sway[1]. However, neural mechanisms require a different control for these muscles. According to a previous paper[16], SOL or GL during postural fluctuation without conscious effort could be explained by spinal mechanisms, however, corticospinal excitability of TA is enhanced with postural fluctuation during standing. The study using transcranial magnetic stimulation (TMS) over the primary motor cortex (M1) showed that the excitatory signals to the corticospinal pathway in TA was increased in the standing position than while sitting. Moreover, previous work[17] using functional magnetic resonance imaging (fMRI) found that neural activation in M1 was greater for muscle contraction, and the DLPFC conversely had greater activity during muscle relaxation of an isometric pinch grip. Those studies suggest that the excitatory and inhibitory inputs to the motor cortex or the DLPFC contribute substantially to postural control or muscle contraction and relaxation in addition to the cerebellum, brainstem and ganglia. In our study, the larger activity of oxy-Hb in both DLPFC of the L group compared with the S group, though not statistically significant, was probably related to lesser muscle activity of TA. It is possible that the number of participants in this study was insufficient to achieve the required power of analysis. Notably, the dorsiflexors such as TA are rarely activated and normal postural control occurs automatically, primarily due to plantarflexors in young adults. In healthy older adults, however, the TA are frequently activated, increasing ankle muscle coactivation during static standing[15]. Interestingly, the participants in S group in this study required TA activity and ankle muscle coactivation for postural steadiness to have similar results as older adults. Although ankle muscle coactivation is likely to be accompanied with an increase in ankle joint stiffness and postural sway in older adults[15], the S group in this study had a decrease in postural sway. We believe that ankle muscle coactivations in the S group may have been associated with multi-segmental movement, which are cooperated with the hips by a mixed strategy or anti-phase action between the legs and trunk, to decrease postural sway by reducing the acceleration of the COP and center of mass (COM); however, older subjects may have difficulties in relying on multi-segmental action[18, 19]. It is known that many older adults use a strategy involving hip movements with ankle coactivation or before ankle movements, because their muscle response organization is disrupted and incapable of synchronously activating proximal and distal muscles with appropriate timing and force, when balance is threatened. It may be necessary to measure the segment-action of the legs and trunk during tasks to investigate the relationship between ankle muscle coactivation and multi-segmental movement. Future studies should investigate whether ankle muscle coactivation relies on multi-segment movement for postural stability, not only in the young, but also in older adults during the performance of dual-tasks. The most obvious limitation in this study was its small sample size, which may limit how generalizable the results are to young adults.

This study investigated whether the DLPFC, ankle muscle activation, and muscle coactivation contribute to postural steadiness during dual-task performances. We found that the blood flow in the left DLPFC increased during posture-calculating dual-task, but postural sway did not. Comparing the S group and L group trajectory lengths to its corresponding single-task, different ankle muscle activation patterns were indicated for posture steadiness. Further studies are needed in order to elucidate the age-related effects of the DLPFC and ankle activities, including ankle coactivation, during the performance of dual-tasks.

Conflict of interest

The authors have no conflicts of interest to declare.

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