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Neuromuscular Control of the Agonist–Antagonist Muscle Coordination Affected by Visual Dimension: An EMG-fNIRS Study

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ABSTRACT Motor planning can enable integration of sensory input to generate motor execution. However, how the brain analyses visual information and modulates its signals to the muscle have been not well studied in human. The aim of this study was to investigate the dimensionality effect of myoelectric-controlled interface (MCI) on motor planning and motor execution during elbow tracking movements. Twenty right-handed healthy subjects were recruited to complete tracking tasks by modulating their biceps and triceps activation within one-dimensional and two-dimensional MCI. The electromyography (EMG) signals of the biceps and triceps was recorded to calculate the normalized muscle activation, while the functional near infrared spectroscopy (fNIRS) signals of the prefrontal cortex (PFC) and bilateral motor cortex (MC) were also collected to gain the brain activation simultaneously. The results showed that the activation of antagonist muscle was significant lower within two-dimensional MCI than that within one-dimensional MCI at the muscle level. At the brain level, it was found an obvious higher activation in the PFC and the left MC within two-dimensional MCI than that within one-dimensional MCI. The current EMG-fNIRS study confirmed that visual feedback can influence motor planning and motor execution, and the PFC and bilateral MC are the likely targeted sites of the proactive inhibition of the antagonist muscle. This study adds a new perspective to possible visual regulation of neuromuscular control, which might be an effective rehabilitation method to improve abnormal muscle coordination in the clinic.

INDEX TERMS Cortical oxygenation, function near-infrared spectroscopy, muscle coordination, visual feedback.

I. INTRODUCTION

Neuromuscular control results from intricate dynamic interactions among sensory input, motor planning and motor execution [1]. Sensory input which is required to define the body posture in the beginning and to monitor the body trajectory during the progress of the task in order to correct the movement trajectory is important for motor planning and motor execution [2]–[4]. Motor planning reflects the brain activation related to the decision and selection of goals and strategies and generates motor command appropriate for motor execution. Motor command is relayed to the muscles and produce movement [5].

Visual feedback is one of sensory inputs to monitor the process of motor execution [6], [7] and myoelectric-controlled interface (MCI) is a kind of visual feedback tool, which can map the electromyography (EMG) signal of muscle to cursor movement and enables the subjects to flexibly modulate their muscle activation patterns. MCI has been applied in rehabilitation and proven effective to improve abnormal muscle co-activation [8]. Young *et al.* used a two-dimensional MCI to investigate the role of MCI on the elbow antagonist muscle, and the result showed that MCI could be a method to decrease the activation of antagonist

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muscle [9]. In addition, both Radhakrishnan *et al.* and Wright *et al.* showed that the muscle co-activation patterns could be modulated within a two-dimensional MCI in healthy subjects [10], [11]. Luo *et al.* has compared the dimensionality effect of MCI on muscle co-activation between healthy subjects and patients after stroke [12]. These studies demonstrated that users could be able to activate muscles independently and modulate muscle co-activation patterns within two-dimensional MCI, which was an evidence of the modification of motor execution affected by two-dimensional MCI.

Muscle activation is closely linked to the cortical excitability, and some studies have explored brain activation during motor tasks. The brain activation in a motor planning phase can be monitored by functional magnetic resonance imaging (fMRI), electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) during motor tasks, for example, hand grasping [13], arm movement [14], finger movement [2]. The major advantages of fNIRS over fMRI and EEG are its good time resolution [15] and spatial resolution [16], respectively. In recent years, fNIRS has been widely used to study functional activity of the human cerebral cortex during different motor tasks. The results of previous fNIRS studies had shown relative the concentration of oxygenated hemoglobin (HbO) signal increased in several brain regions [17], [18], including the PFC [14] and the primary motor cortex (MC) [19], [20]. An EEG study had shown that movement-related brain regional activation was predominant over the primary motor cortex [21], which revealed that motor execution likely relied on the engagement of MC. Motor execution is an umbrella term including cognitive processes and related behaviors, such as target prediction, motor monitoring, motor inhibition and motor planning [22]. It was noted that motor planning is an ability about anticipating motor demands and PFC plays a critical role in motor planning [23]. Extensive neuroimaging researches have demonstrated that concurrent activation in the PFC and MC while motor planning [24], [25] and execution [26].

So far, our previous study had found the significant decreases in the activation of agonist and antagonist muscles with the increase of visual dimension during isometric elbow extension [12]. Although motor planning was reported to be associated with motor execution according to visual feedback [18], [21], [27], [28], it was still unknown where and how motor planning response to the process of changing visual dimension. The aim of this study was to investigate the dimensionality effect of MCI on motor planning and motor execution during visually guided elbow tracking movement. In one-dimensional and two-dimensional tasks, the fNIRS and EMG signals were monitored to gain the brain and muscle activation, respectively. We hypothesized that there would be distinct different brain and muscle activation pattern due to the increase of visual dimension, signifying a change in motor planning and motor execution. This study might provide a comprehensive aspect to understand the underlying interactions among visual feedback, motor planning and motor execution.

II. METHODS

A. PARTICIPANTS

Twenty self-reported right-handed healthy volunteers (15 females, 5 males, mean age: 23.9 ± 1.86 years) participated in this study. The subjects were excluded for any history of musculoskeletal or neurological disorders. All subjects were informed about the experimental details of this study and signed the consent form before the experiment. The study was approved by the ethic committee of Guangdong Work Injury Rehabilitation Center.

B. EXPERIMENTAL PROCEDURES

The experimental device was displayed in figure 1a. After understanding the whole experimental protocol, each subject was required to sit straightly in an adjustable chair and face to a computer screen. The right-arm of each subject was horizontally set in the armrest which was located on the right side of the subjects. Firstly, each subject was instructed to perform

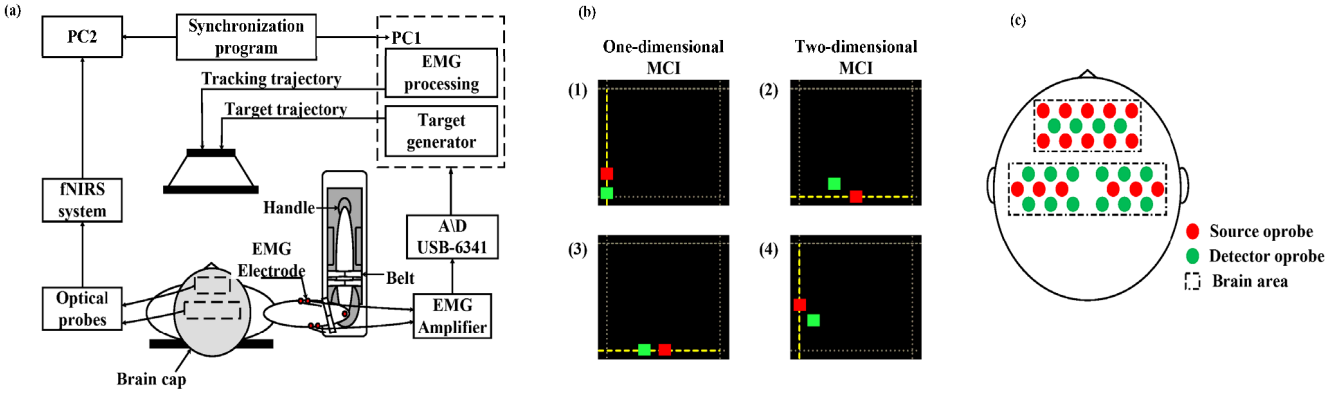

FIGURE 1. The experimental setup: (a) Schematic representation of the experimental protocol; (b) Schematic of two different visual feedback dimensions: (1) and (3) respectively showed the tracking tasks during elbow flexion and extension within one-dimensional MCI; (2) and (4) respectively showed the tracking tasks during elbow flexion and extension within two-dimensional MCI; (c) Schematic illustration of fNIRS layout: 36 channels,16 sources and 16 detectors.

5-s maximal voluntary contraction (MVC) tasks which was including elbow flexion and extension and repeated three times. There was a 2-min rest between each time to avoid muscle fatigue. The maximal values of biceps (BIC) and triceps (TRI) EMG signals were measured in the MVC tasks and used to normalize the EMG signals in the following tracking task that included four tracking conditions: 1) isometric elbow flexion within one-dimension MCI; 2) isometric elbow extension within one-dimension MCI; 3) isometric elbow flexion within two-dimension MCI; 4) isometric elbow extension within two-dimension MCI. Each subject was asked to track the target by modulating BIC and TRI activation according to the visual feedback under different tracking conditions. There were three tracking trials in each tracking condition and between each trial there was 2min to rest. Each tracking trial included a 7-s prepare period, 60-s tracking period and 10-s relax period. In the tracking period, the maximal contraction level was set at 10% of each subject's maximal values of BIC and TRI to avoid fatigue. Specially, previous study reported that there was 3∼5s delay in hemodynamic responses [29], so the subjects were required to avoid moving head and trunk to avoid unnecessary movement artifacts in the fNIRS signals in the relax period. Moreover, the subjects were required to avoid undesired saccadic eye movement in the whole experiments.

The design of MCI was described in figure 1b, including a red sliding cursor and a green sliding cursor. The red sliding cursor was the tracking target, moved according to the presupposed trajectory at a constant velocity. In the training trial, the activating muscles were mapped separately along two orthogonal directions (vertical and horizontal directions). During elbow flexion, tracking target would vertically move along the direction of BIC from the initial point (0, 0) to the destination (0, 10%MVC) and then returned to the initial point in 20s as a cycle which was repeated three times in each trial. When the subjects performed the isometric elbow extension tasks, the tracking target would horizontally move along the direction of TRI from the initial point (0, 0) to the destination (0, 10%MVC) and then returned to the initial point in 20s as a cycle which was repeated three times in each trial. Each subject could control the green sliding cursor according to the activation of agonist and antagonist muscles. Within one-dimensional MCI, the position of green sliding cursor was concerned only with the activation of agonist muscle. Within two-dimensional MCI, the EMG signals of both agonist and antagonist muscles were necessary to form the control signal of the green sliding cursor, which meant that the green sliding cursor could move across the whole screen (a two-dimensional plane). Therefore, the subject was required to proactively inhibit the activation of antagonist muscle and modulate the activation of agonist muscle to track the target in two-dimensional task.

C. DATA ANALYSIS AND PROCESSING

After cleaning skin with alcohol, several disposable Ag–AgCl bipolar electrodes with a diameter of 50 mm and an inter-electrode distance of 20 mm were placed over to the belly of BIC and TRI. During elbow flexion, BIC and TRI were as the agonist and antagonist muscles, respectively. When the subjects performed isometric elbow extension tasks, the contribution of BIC and TRI would exchange. The EMG signals of BIC and TRI were collected by a two-channel customized EMG amplifier, with a gain of 5000 and sampled at 1000 Hz by a data acquisition card (DAQ-6341, National Instruments, Austin, TX, USA). A customized program in LabVIEW^{TM} (LabVIEW 2012, National Instruments, Austin, TX, USA) was applied to store the raw EMG signal and provide the real-time visual feedback in the computer.

In this study, the hemodynamic responses in the PFC and bilateral MC of each subject was recorded by a commercial fNIRS equipment (NirSmart, Danyang Huichuang Medical Equipment Co. Ltd., Beijing, China). Sixteen source probes and sixteen detectors were placed on a customized brain cap fixed over the head of each subject to adapt the cap to the individual size and shape of head. The detector-source probe distance was 30mm apart. The locations of source probes and detectors in this study were shown in figure 1c. A source probe and a detector could form an fNIRS channel so that there were 36 channels designed in this study. To cover the PFC and MC of both hemispheres, the source probes and detectors were arranged in three groups clustered around positions Fp1, Fp2, C3 and C4, referring to the international EEG 10-20 system [30]. The fNIRS system was collected at a sample rate of 10 Hz at near-infrared light at wavelengths of 760 and 850 nm. The EMG signals and fNIRS signals were recorded simultaneously with a customized synchronization program in LabVIEW^{TM}.

All the data analysis was done using MATLAB (MathWorks^{TM} Inc., Massachusetts, USA). The raw EMG signals in the tracking period were firstly band-filtered by 4th-order Butterworth filter (20-450Hz), and then normalized the filtered EMG signals using maximal values of BIC and TRI. The root mean square (RMS) of EMG signal was applied to represent muscle activation. To investigate the activation of agonist and antagonist muscles in different tracking conditions, RMS of EMG signals was calculated as the following formula:

$$RMS = \sqrt{\frac{\sum_i y(i)^2}{N}} \tag{1}$$

where $y(i)$ was the filtered EMG signals ($i = 0, 1, \ldots, N-1$) and N represented the length of the filtered EMG signals.

The fNIRS data in the PFC and bilateral MC was be extracted from the raw fNIRS signals, including three parts: 1) the last 5-s of the rest period taken as the baseline period; 2) the 60-s of tracking period; and 3) the beginning 5-s of the relax period. The fNIRS data was calculated relative concentration changes according to the modified Beer–Lambert law and then filtered by a Butterworth band-pass filter with a band of 0.002–0.5 Hz. It was reported in the previous study that the HbO was a reliable and sensitive index of locomotion-related changes in the brain activation. Therefore, the concentration

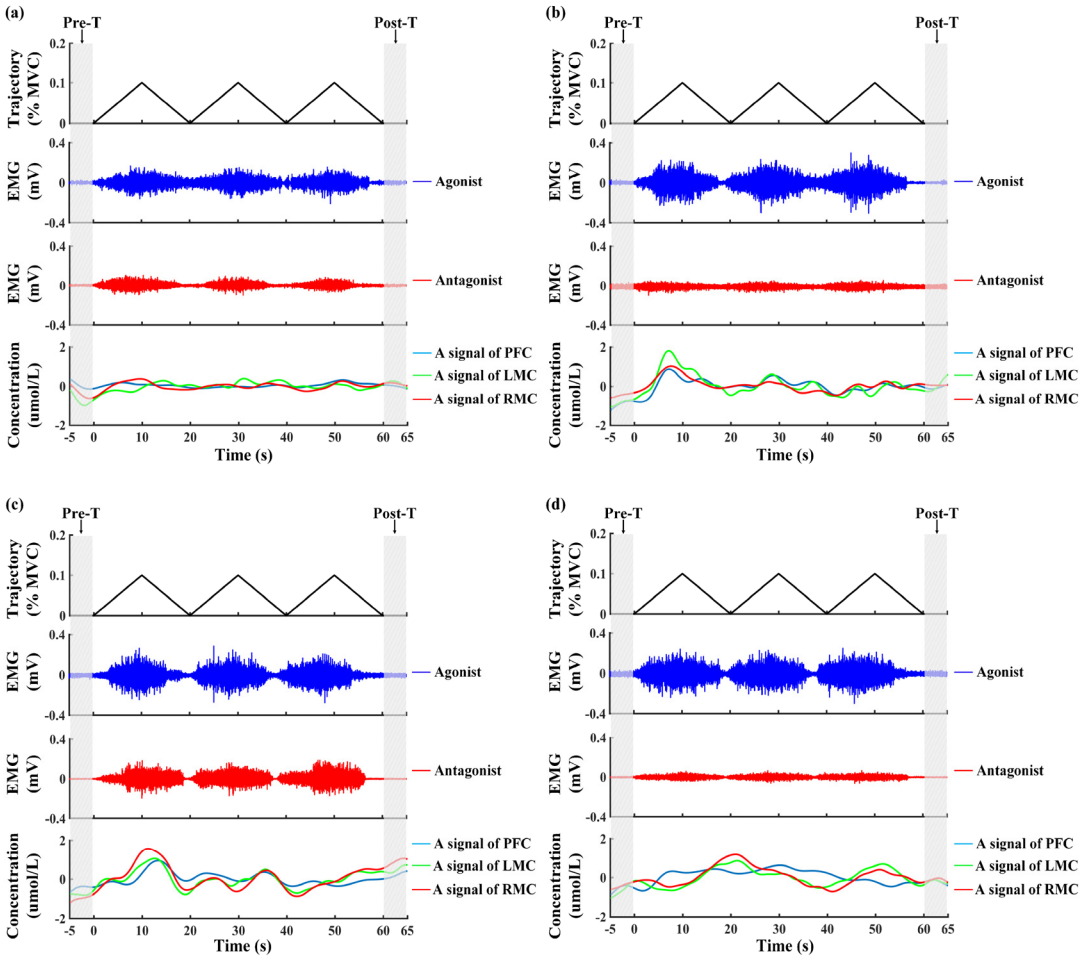

FIGURE 2. Example of EMG and fNIRS data recorded in different tracking conditions; (a) elbow flexion within one-dimensional MCI, (b) elbow flexion within two-dimensional MCI, (c) elbow extension within one-dimensional MCI, (d) elbow extension within two-dimensional MCI. Biceps and triceps respectively worked as agonist muscle during elbow flexion and extension. Time series of HbO at three typical signals in the PFC, LMC and RMC were shown. Notes: Pre-T: the last 5-s of the rest period; Post-T: the beginning 5-s of the relax period; PFC: the prefrontal cortex; LMC: the left primary motor cortex; RMC: the right primary motor cortex.

change of HbO (ΔHbO) was calculated as the following formula:

$$\Delta HbO = HbO_{tracking} - HbO_{baseline} \tag{2}$$

where $HbO_{baseline}$ defined as the mean hemodynamic response during the last 5-s of the rest period. $HbO_{tracking}$ represented the mean hemodynamic response during the 60-s tracking period and the beginning 5-s of the relax period. Furthermore, the ΔHbO of all pairs of source probe and detector within one area were averaged to represent the changes of the brain regional activation.

D. STATISTICAL ANALYSIS

All statistical analyses were calculated with the SPSS statistical software (version 22.0, SPSS Inc., Chicago, IL, USA) in this study. All parameters were reported as means ± standard deviation (SD) in the figures. The average RMS of all subjects in each tracking conditions was calculated. In order to investigate the effects of dimensionality and tracking direction on the agonist and antagonist muscles, a three-way repeated-measures analysis of variance (ANOVA) was performed with three within-factors: dimensionality (one-dimensional or two-dimensional MCI), tracking direction (elbow flexion or extension) and muscle (agonist or antagonist muscle). When the significance was obtained, a post-hoc paired t-test was applied to identify the significant differences between elbow flexion and extension within each MCI in each muscle.

The average ΔHbO of all subjects in each tracking condition was used in this study. In order to determine whether a response was seen in the hemodynamic response in different tracking conditions, a repeated-measures ANOVA was performed including three within-subject factors: the cortical region (PFC, the left MC or the right MC), the dimensionality (one-dimensional or two-dimensional MCI) and tracking direction (elbow flexion or elbow extension). Bonferroni post hoc analysis was exploited for multiple comparisons. Pair t-tests were performed to evaluate the influence of:

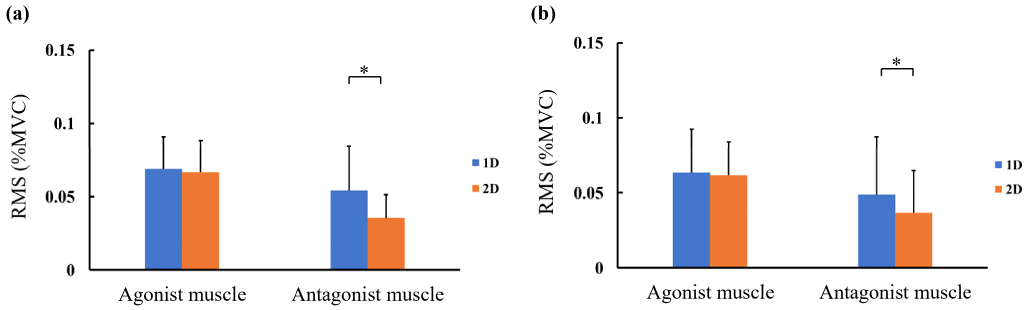

FIGURE 3. The RMS of the agonist and antagonist muscles within one-dimensional (1D) and two-dimensional (2D) MCI during (a) elbow flexion and (b) elbow extension. ∗ Statistically significant difference ($p < 0.05$).

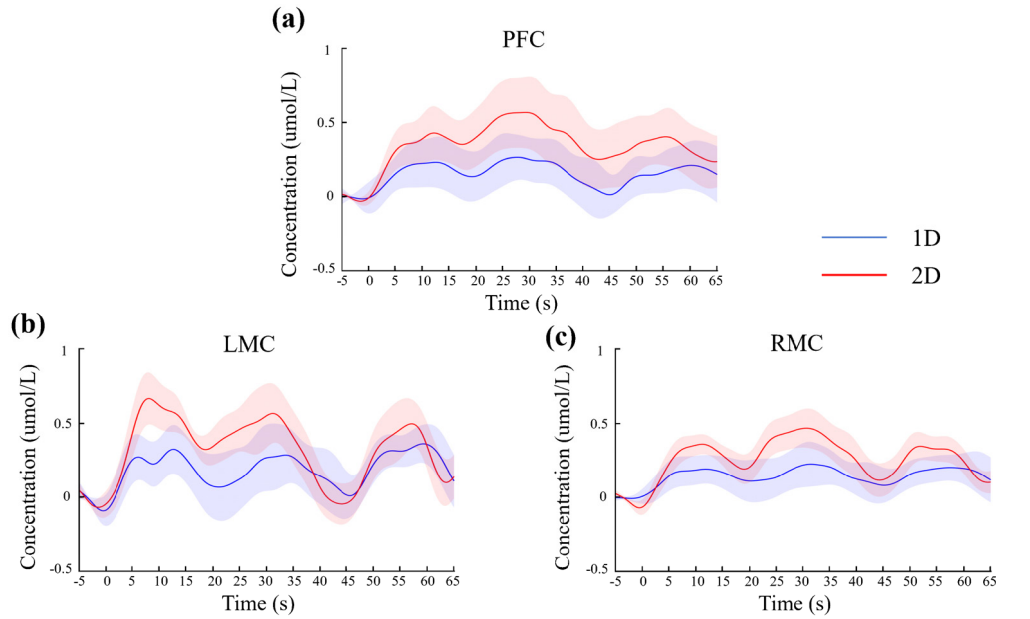

FIGURE 4. Regional changes of ΔHbO (mean ± SD) in the PFC, the left MC (LMC) and the right MC (RMC) during elbow flexion within one-dimensional (1D) and two-dimensional (2D) MCI. The blue and red solid lines represent the mean activation within one-dimensional (1D) and two-dimensional (2D) MCI, respectively.

1) the dimensionality effect of MCI (one-dimensional or two-dimensional MCI) on the PFC and bilateral MC activation during both elbow flexion and extension 2) the tracking conditions (elbow flexion or elbow extension) on the PFC and bilateral MC activation within each MCI. In this study, data was analyzed and reported as the means ± standard deviations (SD). The results were considered significant when the value of p was < 0.05 for all the statistical analysis.

III. RESULTS

A graphical representation of tracking trajectory, the raw EMG signals and fNIRS signals within one-dimensional and two-dimensional MCI during elbow flexion and extension were displayed in figure 2, respectively.

RMS represented the muscle activation during tracking trials and revealed the following results in this study. Figure 3 showed the averaged RMS of agonist and antagonist muscles in different tracking conditions. Results of three-way ANOVA analysis displayed that there was no specific effect of tracking direction on RMS ($p = 0.408$) and no significant interaction among three factors (dimensionality ∗ tracking direction: $p = 0.681$, dimensionality ∗ muscle: $p = 0.115$, muscle ∗ tracking direction: $p = 0.688$). The significant effects of dimensionality ($p = 0.038$) and muscle ($p = 0.008$) were found. The results of post hoc analysis showed that RMS of antagonist muscle was significantly lower within two-dimensional MCI than that within one-dimensional MCI. These significant differences were observed during both elbow flexion ($p = 0.038$) and extension ($p = 0.016$). However, for the agonist muscle, there was no significant difference was obtained within different MCIs ($p = 0.620$) and tracking directions ($p = 0.410$).

Figure 4 and figure 5 showed the average hemodynamic response in the PFC and bilateral MC during elbow flexion and extension within each MCI, respectively. For elbow flexion, since the beginning of the tracking period, an increase

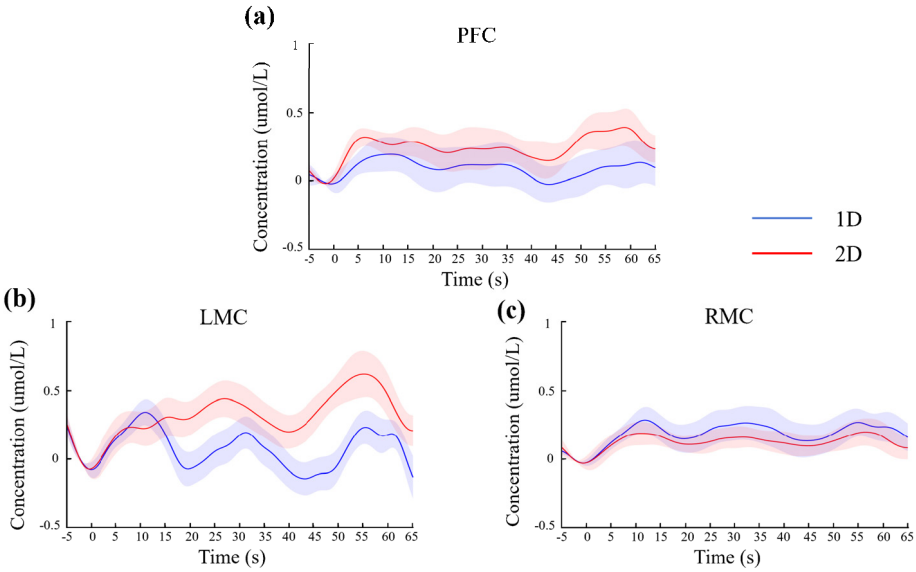

FIGURE 5. Regional changes of ΔHbO (mean ± SD) in the PFC, the left MC (LMC) and the right MC (RMC) during elbow extension within one-dimensional (1D) and two-dimensional (2D) MCI. The blue and red solid lines represent the mean activation within one-dimensional (1D) and two-dimensional (2D) MCI, respectively.

of the ΔHbO in the PFC and bilateral MC was observed both in the one-dimensional and two-dimensional tasks. The PFC and bilateral MC activated more vigorously in the two-dimensional tasks than in the one-dimensional tasks. For elbow extension, a similar, but smaller increase of the ΔHbO was found in the beginning of the tracking period both in the one-dimensional and two-dimensional tasks.

Figure 6 showed the average activation pattern based on the task-related changes of hemodynamic response in different tracking conditions. For elbow flexion, compared to the one-dimensional tasks, the left MC and PFC recruitment

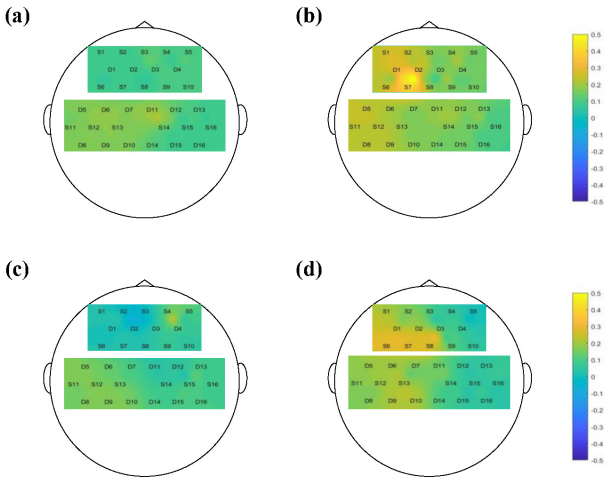

FIGURE 6. The average cortical mapping based on ΔHbO in the PFC and bilateral MC during different tracking conditions: (a) elbow flexion within one-dimensional MCI, (b) elbow flexion within two-dimensional MCI, (c) elbow extension within one-dimensional MCI, (d) elbow extension within two-dimensional MCI.

was more prominent in the two-dimensional tasks. There was a similar result during elbow extension, which showed that the hemodynamic response in the PFC and the left MC increased in the two-dimensional tasks. The differences of average hemodynamic response in four tracking conditions were showed in figure 7, together with the SD along all the subjects. Results of repeated-measures ANOVA analysis on the ΔHbO revealed the significant main effects of the dimensionality ($p = 0.026$) and cortical region ($p = 0.004$). There was no significant difference in tracking directions ($p = 0.460$). The statistical analysis didn't show a significant interaction among three factors (dimensionality $*$ tracking direction: $p = 0.113$, dimensionality $*$ cortical region: $p = 0.161$, cortical region $*$ tracking direction: $p = 0.378$). The result of pair t-tests of ΔHbO showed a significant difference for all the cortical regions in the comparison between one-dimensional and two-dimensional MCI during elbow flexion (PFC: $p = 0.000$, the left MC: $p = 0.041$ and the right MC: $p = 0.016$) and extension (PFC: $p = 0.031$, the left MC: $p = 0.025$ and the right MC: $p = 0.298$), but there was no distinct difference for all the cortical regions in the comparison between elbow flexion and extension within one-dimensional (PFC: $p = 0.536$, the left MC: $p = 0.104$ and the right MC: $p = 0.331$) or two-dimensional MCI (PFC: $p = 0.808$, the left MC: $p = 0.0547$ and the right MC: $p = 0.339$). For elbow flexion, the activation in the PFC and bilateral MC was significant greater in the two-dimensional tasks than that in the one-dimensional tasks. For elbow extension, the activation in the PFC and the left MC significantly increased within two-dimensional MCI. The activation in the left MC appeared to activate stronger than the right MC during both elbow flexion and extension.

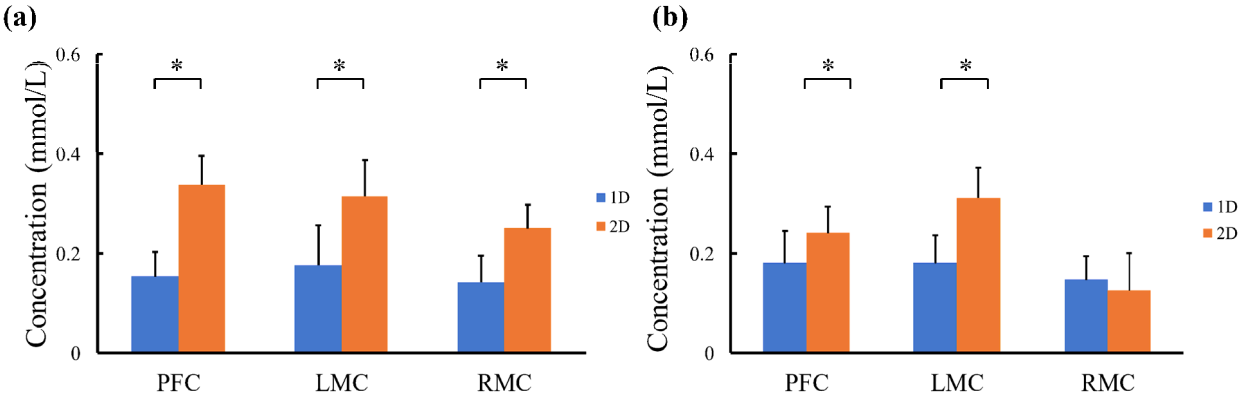

FIGURE 7. The average hemodynamic responses in the PFC and bilateral MC during elbow flexion (a) and elbow extension (b) within each MCI. Notes: 1D: one-dimensional MCI; 2D: two-dimensional MCI; LMC: the left primary motor cortex; RMC: the right primary motor cortex. The asterisk (∗) indicated a significant difference between one-dimensional and two-dimensional MCI ($p < 0.05$).

IV. DISCUSSION

Since visual input could alter both motor planning and execution, the evaluation of EMG signals together with the measurement of fNIRS signals have provided the possibility to both explain the influence of visual dimension on motor planning and execution and indicate the relationship between motor planning and execution. We investigated the dimensionality effect of MCI on motor planning and motor execution during visually-guide tracking in this study. The major finding is that the stronger activation in the PFC was observed when inhibition occurred at the antagonist muscle within two-dimensional MCI.

In order to reduce motor errors, visual feedback was used to update motor planning and adjust motor execution. The muscle activation provided an indicator for examining the dimensionality effects of MCI on motor execution. In this study, the distinct lower activation of antagonist muscle was found in two-dimensional task than that in one-dimensional task, which was in agreement with the results of previous studies [9], [11]. Wright *et al.* mapped five muscles to different directions, and found it was effective to reduce abnormal muscle co-activation by activating muscles independently within multi-dimensional MCI [11]. Young *et al.* suggested that the children with dystonia could adjust their muscle activation and reduce abnormal muscle co-activation with the use of two-dimensional MCI [9]. Aymar *et al.* also found that the increase of task-space dimensionality could change the activation of multiple muscles and muscle activation pattern [31]. The decreasing activation in the antagonist muscle was attributed to the increase of visual dimension in this study. The subjects were able to activate the agonist muscle and suppress the antagonist muscle based on the additional visual input about antagonist muscle under the two-dimensional condition.

Several studies had reported that the coordination of agonist and agonist muscles was related to the mechanism involved in the spinal cord and brain. At spinal level, it has been proposed that muscle inhibition appeared to be affected by the afferent fibers Ia from neuromuscular spindles [32]. On the other hand, descending inputs from several areas of the cerebral cortex, such as the MC and PFC, played an important role in the coordination of agonist and antagonist muscles [33]. The MC is involved in the generation of movement, and the activity of neurons in the MC may encode motor commands for muscles at a single joint [34]. It was reported that the cerebral blood flow in the MC covaried with motor execution [35], [36], which might interpret the increase of activation in the MC during elbow flexion and extension in this study. Moreover, a higher activation was found in the left MC than in the right MC during all tracking conditions, as the recruited subjects complete the experiments with their right hands. This finding was consistent with previous study that unilaterally hand movement could cause the activation in contralateral MC [37]. We also found that the activation of the left MC was increased during the two-dimensional task in comparison to the one-dimensional task. One possible explanation could be that the tasks within two-dimensional MCI became more complex than within one-dimensional MCI. A TMS study reported a similar result that performing complex upper limb motor tasks, as opposed to simple ones, required additional activations in the left MC [38]. This change in the activation in the left MC during complex task might be associated with the changes in the numbers of motoneurons that project to the agonist and antagonist muscles motoneuron pool and the differences in size of the strength of the motoneuron cells recruited [39]. Therefore, the significant higher activation in the left MC within two-dimensional MCI in this study indicated that the motoneurons in the left MC might activate more during controlled precision movement. Another evidence suggested that the increase in the activation in the MC was related to the decreased activation of antagonist muscle [40]. Within the two-dimensional MCI, the decreasing activation of antagonist muscle could reflect that the antagonist muscle was actively inhibited, which was modulated by the central nervous system [41]. Such modulation may descend from the MC to the motoneuron of the antagonist muscle [42].

On the other hand, performing motor tasks requires the activations in subcortical or cortical regions other than the MC and the communications among brain areas. The MC is thought to connect with the other brain areas via several potential pathways during executive processes [43], such as the PFC which is an integration of interconnected cortical areas. Narayanan *et al.* had proposed that there was a top-down control signal in the interaction between the dorsomedial PFC and the MC during a delayed-response task [44]. The dorsomedial PFC might achieve modulation of the discharge of motor cortical neurons through extensive connections with striatum, thalamus and the limbic system [45]–[47]. In this study, the result showed that the enhanced activation in the left MC was associated with the increasing activation in the PFC, indicating a connection between the PFC and MC.

Moreover, previous study had demonstrated that the PFC was critical for hierarchically coordinating and planning motor execution [48]. The task-based fMRI studies found that the activation in the PFC was associated with both visual inputs and motor execution [49], [50]. These studies suggested that the PFC played an important role in motor planning and influenced by visual inputs. In this study, the activation in the PFC was higher in the two-dimensional task than that in the one-dimensional task, revealing that the subjects increased the recruitment of the PFC in response to the additional visual input within two-dimensional MCI, which could increase cognitive workload and consequently caused the higher neural activity in the PFC [51]. Liu *et al.* pointed out that the hemodynamic activation in the PFC showed an increasing tendency with the increase of cognitive workload [52]. Basso *et al.* testified that the activation in the PFC was related to the difficulty level of the task, since the harder task could incur more cognitive workload and then require higher activation in the PFC [53]. Thus, the PFC might be involved in the monitoring of visual input in order to modulate motor planning by integrating spatial and temporal information, which was help to prepare specific motor execution [54]. Another view was proposed that the significant higher activation in the PFC found from two-dimensional to one-dimensional MCI could be attributed to not only excitatory, but also inhibitory function in the PFC. Some regions in the PFC might be specialized for supporting inhibition of inappropriate muscle responses [55]. Motor inhibition might originate from the PFC [56], and the activation in the PFC would increase during motor inhibition [57]. As mentioned above, compared to one-dimensional MCI, two-dimensional MCI could provide additional visual feedback about the activation of antagonist muscle, which suggested the subjects to suppress their antagonist muscle. Therefore, the increase of activation in the PFC and the decrease of antagonist muscle activation within two-dimensional MCI might provide the evidence of the motor inhibition of antagonist muscle affected by the increase of visual dimension.

The EMG-fNIRS system [38] in this study could provide comprehensive information regarding motor planning and motor execution in response to different MCI dimensions during visually-guide training, which might have clinical potential for evaluation of neuromuscular control of the agonist - antagonist muscle coordination. MCI is an advanced technology as EMG-driven virtual feedback tool, which was widely used in clinical assessment and rehabilitation training. In this study, two-dimension MCI could be used to decouple co-activating muscles and independently activate muscles, and the activation pattern in detected cortices significantly changed within two-dimensional MCI in healthy subjects. Considering the deterioration in coordinating agonist and antagonist muscles in stroke patient, two-dimensional MCI is quite promising in the clinical evaluation of the coordinating agonist and antagonist muscles. Two-dimensional MCI might also offer a new rehabilitation therapy for stroke patients to improve muscle coordination. Therefore, future studies on stroke patients would be necessary to confirm the dimensionality effect of MCI on muscle coordination and evaluate the therapeutic effect of rehabilitation therapy. The primary limitation of this study was that the hemodynamic response in whole brain area was not measured during the tracking trial since other brain regions has been proposed to be involved in this process, especially premotor cortex, cerebellum and parietal lobe [58]. In future work, it will be necessary to analyze more brain regions and the functional connectivity among brain regions. Moreover, future work should investigate the correlation between EMG and hemodynamic signals, which can contribute to further explore the different effects of dimensionality on muscle coordination in healthy subjects.

V. CONCLUSION

In this study, the EMG-fNIRS system was utilized to investigate the dimensionality effect on motor planning and motor execution based on MCI during visually-guide tracking. The significant reduced activation of antagonist muscle might be related to the increase of activation in the PFC and the left MC within two-dimensional MCI, which indicated motor inhibition involved in suppressing the activation of antagonist muscle. Thus, this study could be able to provide a comprehensive insight into motor planning and motor execution towards different visual dimensions, which might be an effective rehabilitation method to improve abnormal muscle coordination in the clinic.

AUTHOR CONTRIBUTIONS

Rong Song designed the work, revised and determined the final manuscript. Chuyao Jian designed the work, collected and analyzed the data, and drafted and revised the manuscript. Linchuan Deng and Xiaoyun Wang collected the data. Liuke Liang and Jie Luo explained the result and revised the manuscript.

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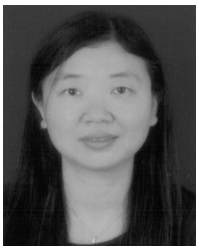

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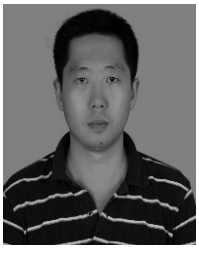

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