

Title: The influence of unilateral contraction of hand muscles on the contralateral corticomuscular coherence during bimanual motor tasks

Running head: Corticomuscular coherence during bimanual motor tasks

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Abstract

The mechanisms behind how muscle contractions in one hand influence corticomuscular coherence in the opposite hand are still undetermined. Twenty-two subjects were recruited to finish bimanual and unimanual motor tasks. In the unimanual tasks, subjects performed precision grip using their right hand with visual

feedback of exerted forces. The bimanual tasks involved simultaneous finger abduction of their left hand with visual feedback and precision grip of their right hand. They were divided into four conditions according to the two contraction levels of the left-hand muscles and whether visual feedback existed for the right hand. Measures of coherence and power spectrum were calculated from EEG and EMG data and statistically analyzed to identify changes in corticomuscular coupling and oscillatory activity. Results showed that compared with the unimanual task, a significant increase in the mean corticomuscular coherence of the right hand was found when left-hand muscles contracted at 5% of the maximal isometric voluntary contraction (MVC). No significant changes were found when the contraction level was 50% of the MVC. Furthermore, both the increase of muscle contraction levels and the elimination of visual feedback for right hand can significantly decrease the corticomuscular coupling in right hand during bimanual tasks. In summary, the involvement of moderate left-hand muscle contractions resulted in an increase tendency of corticomuscular coherence in right hand while strong left-hand muscle contractions eliminated it. We speculated that the perturbation of activities in one corticospinal tract resulted from the movement of the opposite hand can enhance the corticomuscular coupling when attention distraction is limited.

Keywords

Corticomuscular coherence; bimanual; oscillations; electroencephalography; electromyography

1. Introduction

The synchronized discharge of corticospinal cells is believed to be reflected by the coherent activities of the beta band (15-30 Hz) between the motor cortex and the muscles (S N Baker, Olivier, & Lemon, 1997; Conway, et al., 1995). The information from the synaptic drive to spinal motoneurons during a voluntary contraction can be evaluated by estimating the coherence (Stuart N Baker, 2007; Witham, Wang, & Baker, 2010) which measures the strength of coupling between signals in the frequency domain (Rosenberg, Amjad, Breeze, Brillinger, & Halliday, 1989). Coherence analysis for monkeys (S N Baker, Kilner, Pinches, & Lemon, 1999; S N Baker, et al., 1997; Murthy & Fetz, 1992, 1996; Witham, et al., 2010) and humans (Halliday, Conway, Farmer, & Rosenberg, 1998; Kilner, Baker, Salenius, Hari, & Lemon, 2000; Kristeva, Patino, & Omlor, 2007; Riddle & Baker, 2006) in previous studies has demonstrated that synchronization between cortical and contralateral muscle activities is most pronounced in the beta-band range during steady muscle contractions. Coherence in the beta band is also assumed to be associated with strategies for controlling submaximal muscle forces (Conway, et al., 1995; Halliday, et al., 1998; Kilner, et al., 2000).

The mechanisms underlying corticomuscular coupling are still being discussed, and detailed understanding of such mechanisms will greatly enhance their research potentials (Boonstra, 2013). Previous studies mainly focused on the features of corticomuscular coherence (CMC) retrieved from electroencephalography (EEG)/magnetoencephalography (MEG) and electromyography (EMG) analysis during

unimanual motor tasks in healthy individuals. Several factors that influence the corticomuscular coherence have been identified, such as the strength level of contractions (Kilner, et al., 2000; Omlor, Patino, Mendez-Balbuena, Schulte-Mönting, & Kristeva, 2011; Witte, Patino, Andrykiewicz, Hepp-Reymond, & Kristeva, 2007), attention (Johnson, Wheaton, & Shinohara, 2011; Kristeva-Feige, Fritsch, Timmer, & Lücking, 2002), age (Johnson & Shinohara, 2012), frequency of modulated forces (Naranjo, et al., 2010) and motor learning (Mendez-Balbuena, et al., 2012; M A Perez, Lundbye-Jensen, & Nielsen, 2006). Studies based on clinical populations have shown that weakened corticomuscular coherence may reflect an underlying mechanism that produces motor deficits of the post-stroke (Fang, et al., 2009; T Mima, Toma, Koshy, & Hallett, 2001).

Bimanual motions are important for humans because many daily-life tasks require effectors of both hands to produce different and coordinated motor outputs that are usually bound together by an object-directed goal. Thus, studying the corticospinal outputs during bimanual tasks is of great significance. Previous studies that used transcranial magnetic stimulation have demonstrated that the corticospinal output measured in a voluntarily active arm may be changed by the voluntary contraction of an opposite arm muscle (Netz, Ziemann, & Hömberg, 1995; Stinear & Byblow, 2004; Yedimenko & Perez, 2010). Gross et al. (Gross, et al., 2005) demonstrated that the corticomuscular coherence in one hand may be modulated by the direction of the opposite hand's movement. Some studies obtained seemingly contradictory results about how the contractions and contraction level of hand

muscles can influence the corticomuscular coherence in the opposite hand with voluntary contractions (Johnson & Shinohara, 2012; Johnson, et al., 2011; Monica A. Perez, Soteropoulos, & Baker, 2012). Johnson et al. (Johnson, et al., 2011) concluded that the beta-band corticomuscular coherence in one hand decreased during the concurrent movement of the opposite hand due to the divided attention. On the contrary, Perez's study (Monica A. Perez, et al., 2012) showed that the beta-band corticomuscular coherence in one hand increases along with the contraction level of muscles from the opposite hand. She speculated that the complexity of controlling a fine motor task with one hand was increased by the diffuse mirrored activity induced by the strong muscle contraction from the opposite hand. Thus, the corticomuscular coupling needed for fine motor control was increased (Monica A. Perez, et al., 2012). The contradictory results were possibly caused by the different details of their experimental designs. However, the two inferred reasonable factors, namely, divided attention and diffuse mirrored activities, clearly have opposite effects. This difference reflects the complexity of the corticospinal output during bimanual tasks.

This study aimed to verify how the voluntary contraction of hand muscles can influence corticomuscular coherence in the opposite hand that is also performing a voluntary muscle contraction. Considering the results of previous studies (Johnson, et al., 2011; Monica A. Perez, et al., 2012), we attempted to analyze the effects of simultaneous divided attention and other possible mechanisms during bimanual motor tasks, as well as identifying whether a dominant factor is present.

2. Materials and methods

2.1 Experimental paradigm

As the baseline condition, the unimanual task was designed as a precision grip, with the index finger and the thumb of right hand squeezing a strain gauge to exert a 2-N constant force [Figure 1(b)]. During bimanual tasks, subjects were instructed to perform a finger abduction motion with the index finger of their left hand by squeezing another strain gauge [Figure 1(c)] simultaneously with the precision grip motion described above. Visual feedback on the magnitude of exerted and target forces for both hands [Figure 1(d)] was shown on a 19" monitor placed approximately 100 cm in front of the subjects [Figure 1(a)]. Two contraction levels for left-hand muscles were identified, i.e. 5% and 50% of the maximal isometric voluntary contraction (MVC), which was measured before the experiment for each subject. The 5% MVC level **can be** easily achieved by the left hand. Thus, this level was selected to involve left-hand motions without dividing the attention from the control of precision grip with right hand. By contrast, finger abduction at 50% MVC level was more complex and effortful. Thus, more attention had to be divided from the control of precision grip and directed toward the control of finger abduction with left hand. To further divide the attention for adjusting the muscle contractions of right hand, the visual feedback for right hand was eliminated in some bimanual conditions. Thus, four combined conditions were obtained for bimanual tasks based on the contraction level of left-hand muscles and whether visual feedback was retained for the right hand. The conditions were named 'RF-L5', 'R-L5', 'RF-L50' and 'R-L50', where 'RF'

meant visual feedback for right hand was retained; ‘R’ meant visual feedback for right hand was eliminated. ‘L5’ meant the target force for left hand was 5% of MVC and ‘L50’ meant the target force was 50% of MVC. Meanwhile, the unimanual task was termed as ‘RF-L0’.

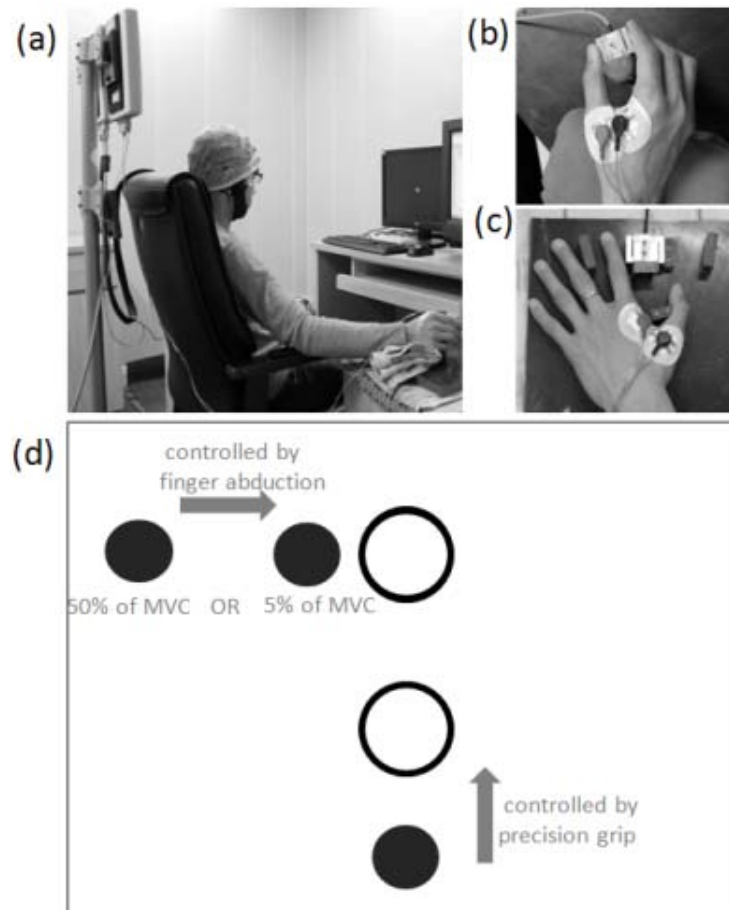


Figure 1. Experimental paradigms and the visual feedback on screen. (a) The experiment was conducted in an electromagnetic shielding room. Subjects were seated on a chair with their forearms resting on tables, and their necks resting on a backrest to avoid fatigue and excessive muscle contractions. A screen was placed 100 cm in front of the subjects to provide them visual feedback of their exerted forces with hands. (b) In both unimanual and bimanual tasks, subjects were instructed to perform a precision grip using the thumb and index fingers of their right hands. (c) In bimanual tasks, subjects were instructed to simultaneously perform an abduction of index

fingers of their left hands in addition to the right-hand motion. EMG signals were obtained from the first dorsal interosseous (FDI) muscles of both hands. (d) A trial was initiated when the lower vertically shifting circle and target ring showed on screen in unimanual tasks or both the lower circle and ring and the upper horizontally shifting circle and target ring showed on screen in bimanual tasks. The positions of target rings were fixed. Subjects were instructed to move the circles into the corresponding rings as soon as possible and maintain the contraction until the end of the trial when all feedback information disappeared. The horizontally shifting circle was controlled by the finger abduction of the left hand. The initial positions varied in different trials corresponding to target forces of 5% or 50% MVC. The vertically shifting circle was controlled by the precision grip of the right hand. The initial position was fixed corresponding to a target force of 2 N. In the steady-hold periods of task 'R-L5' and 'R-L50', the lower horizontally shifting circle and the target ring would disappear.

In both unimanual and bimanual tasks, each trial lasted for 6 s. During the first 2 s, subjects needed to adjust the exerted force on the targets. Then, they were instructed to maintain the force until the end of a trial. For both unimanual and bimanual tasks, the first 2 s of a trial was the adjusting phase and the last 4 s was the steady-hold period. The elimination of visual feedback for right hand only occurred during the steady-hold period. Subjects needed to finish one block of unimanual tasks consisting of 60 trials and seven blocks of bimanual tasks consisting of 40 trials each. In each bimanual block, there were 10 trials for each of the 4 conditions that were distributed randomly. The time interval between two adjacent trials was approximately 2 s. To avoid muscle fatigue, several minutes of rest between two blocks were provided for

the subjects. Subjects practiced before the experiments until target forces could be reached within the adjusting phase as required.

2.2 Recordings

Data recordings were performed in an electromagnetic shielding room. High-resolution EEG was recorded with a SynAmps² system (Neuroscan, El Paso, TX, USA). An elastic cap with 64 mounted Ag/AgCl electrodes positioned according to the extended 10-20 system was used to detect EEG activities with the reference at the vertex. The electrode impedances were maintained under 5 K Ω during the whole experiment. EMG was recorded from the right and left first dorsal interosseous (rFDI and lFDI) muscles using adhesive surface electrodes with 2-cm inter-electrode distance. The EMG signal was amplified using the bipolar channels of the SynAmps² system. The ground electrode, common for EEG and EMG, was positioned on the midline of the scalp at the level of the prefrontal cortex. EEG and EMG signals were amplified (EMG: band pass, 5 Hz to 100 Hz; EEG: band pass, DC to 100 Hz) and sampled to disk at 1000 Hz together with event markers to synchronize with force signals. Force data were recorded simultaneously from two strain gauges at a sampling rate of 200 Hz. All signals were saved on a hard disk for off-line analysis.

2.3 Participants

Twenty-two healthy volunteers (mean age, 20; range, 18–23; 21 right-handed) with normal or corrected-to-normal vision participated in the bimanual tasks. Seventeen of them (mean age, 21; range 19–23 years, 17 right-handed) also took part in the unimanual task. The subjects did not have any known neurological pathology.

Their handedness was confirmed through a systematic questioning about daily manipulations called Edinburgh Handedness Inventory (Oldfield, 1971). The average laterality score for 21 right-handed subjects was 95.23 ± 4.85 . The score for the left-handed subject was -88. All the subjects participated in the experiment with the informed consent and approval of the local ethics committee.

2.4 Data analysis

Two simple procedures were performed to preprocess the raw EEG and EMG data using the EDIT4.3 software (Neuroscan, El Paso, TX, USA). First, raw EEG and EMG signals were high-pass filtered using a zero-phase FIR filter with the cut-off frequency at 1 Hz. Ocular artifacts were then reduced. EEG channels that always contained too much noise were eliminated for further analysis. An open-source MATLAB toolbox, FieldTrip (Oostenveld, Fries, Maris, & Schoffelen, 2011), was used to estimate the power and coherence spectrum for neurophysiological data analysis.

2.4.1 Extraction of EMG activity and force data

To determine the relative activation level of muscles, EMG signals were analyzed in the time domain for each subject and each task. The procedures were similar to a previous study (Chen, Entakli, Bonnard, Berton, & Graaf, 2013). The EMG signals were filtered using a two-pass Butterworth filter between 10 Hz and 100 Hz and then rectified by taking the absolute values. The rectified EMG signals were further filtered using a low-pass filter at 2 Hz.

Afterwards, the EMG activities and force data during the steady-hold periods

were segmented into four non-overlapped 1-s-long segments. Some segments were eliminated when their corresponding EEG segments had obvious noises, which will be described in the next section. The EMG activities and force data were then averaged across samples within each segment and averaged across all remaining segments for each task. The average measures of all subjects were used to perform group-level statistical analysis to verify whether significant changes in right-hand muscle activations occurred between different tasks.

2.4.2 Preprocessing of EEG and EMG

EEG and EMG data within steady-hold periods during which the strongest CMC was always obtained (S N Baker, et al., 1997; Kristeva, et al., 2007; Riddle & Baker, 2006) were used for further analysis. The resulting data were also segmented into four non-overlapped 1 s-long segments with a frequency resolution of 1 Hz. Then, the segments were sorted into five groups according to their corresponding task types. The segments were excluded artificially when EMG or other artificial noises contaminated the EEG signals. Next, the segmented EEG data were transformed into the reference-free current source density (CSD) distribution using the scalp surface Laplacian, which was widely used for corticomuscular coherence analysis in previous studies (Andrykiewicz, et al., 2007; Boonstra, van-Wijk, Praamstra, & Daffertshofer, 2009; Graziadio, et al., 2010; Tatsuya Mima & Hallett, 1999; Muthuraman, et al., 2012). Scalp surface Laplacian removes nearly all volume conduction effects (Nunez, et al., 1997) and is a good approximation to be proportional to the dura potential (Nunez, 1987). The CSD distribution was estimated using the spherical spline

interpolation method (Perrin, Pernier, Bertrand, & Echallier, 1989) as implemented in the Fieldtrip toolbox.

The rectification of EMG data is a conventional procedure (Chen, et al., 2013; Johnson, et al., 2011; Lim, Kim, Kim, & Chung, 2014; Mendez-Balbuena, et al., 2012) prior to the estimation of corticomuscular coherence because full-wave rectification provides the temporal pattern of grouped firing motor units (Halliday, et al., 1995). However, it was not performed in the current study because EMG rectification has been shown to be detrimental to CMC estimation (Bayraktaroglu, et al., 2011; McClelland, Cvetkovic, & Mills, 2012; Neto & Christou, 2010; Stegeman, van-de-Ven, van-Elswijk, Oostenveld, & Kleine, 2010).

2.4.3 Estimation of corticomuscular coherence

The coherence function measures the coupling strength between two signals in the spectral domain and is usually expressed as a normalized quantity between 0 and 1 (Challis & Kitney, 1991; Rosenberg, et al., 1989). In this study, corticomuscular coherence was estimated using the multitaper method (Percival & Walden, 1993), which is widely used in corticomuscular coherence analysis (Boonstra, et al., 2009; Chen, et al., 2013; Schoffelen, Poort, Oostenveld, & Fries, 2011). The coherence between signal x and y at frequency f is calculated as follows:

$$Coh_{xy}(f) = \frac{|S_{xy}(f)|}{\sqrt{S_{xx}(f) \times S_{yy}(f)}}$$

where $S_{xy}(f)$ denotes the cross-spectrum averaged across N data segments and is

estimated as $S_{xy}(f) = \frac{1}{N} \sum_{i=1}^N \left(\frac{1}{K} \sum_{k=1}^K F_f(t_k \otimes x_i) F_f(t_k \otimes y_i)^* \right)$. $F_f(t_k \otimes x_i)$ denotes the

Fourier transform of the tapered time series $t_k \otimes x_i$ (t_k is the k th taper) of segment i at frequency f , and $*$ denotes the complex conjugate. $S_{xy}(f)$ reduces the auto-spectrum when x equals y . The CMC spectrum was determined by calculating the coherence between the CSD signal from each EEG electrode and each unrectified EMG signal. Before the statistical analysis, all original CMC values were transformed into Z-score CMC, which has been used by Schoffelen (Schoffelen, et al., 2011) and Chen (Chen, et al., 2013), because the magnitudes of CMC values are subject specific (Mendez-Balbuena, et al., 2012). The transformation formula is:

$$Coh_{z-score}(f) = \frac{Coh(f) - \mu_{Coh}(f)}{\sigma_{Coh}(f)}$$

where $\mu_{Coh}(f)$ denotes the average CMC value across all EEG-EMG channel combinations for a given muscle at frequency f , and $\sigma_{Coh}(f)$ denotes the corresponding standard deviation.

2.4.4 Selection of electrodes of interest

In this study, we focused on the coupling between activities from the primary motor area and the contralateral hand muscle. However, because the strongest coherence in the beta band might show at different electrodes for different subjects, the electrode of interest was defined based on the topographies of the spatial Z-score CMC. The left primary motor area (lM1) included electrodes ‘FC5’, ‘FC3’, ‘FC1’, ‘C5’, ‘C3’, ‘C1’, ‘CP5’, ‘CP3’ and ‘CP1’. Similarly, the right primary motor area (rM1) was defined to include electrodes ‘FC6’, ‘FC4’, ‘FC2’, ‘C6’, ‘C4’, ‘C2’, ‘CP6’, ‘CP4’ and ‘CP2’. For each subject and a given muscle, the mean topography of the spatial Z-score CMC in the beta band across different tasks was first obtained. The

electrode where the maximum of Z-score CMC emerged in the contralateral primary motor area was defined as the electrode of interest. Further statistical analysis was performed using the Z-score CMC between CSD signals from the electrode of interest and unrectified EMG signals from the contralateral FDI muscle. In the succeeding sections, 'lM1-rFDI CMC' was used to denote the corticomuscular coherence between activities in the left primary motor area and the right FDI muscle related to the precision grip. Similarly, 'rM1-lFDI CMC' denoted the corticomuscular coherence between activities in the right primary motor area and the left FDI muscle related to the finger abduction.

2.4.5 Power estimation of EEG and EMG

The power spectrum of EEG and EMG signals was estimated using the multitaper method. Only EEG signals from the electrodes of interest were used. EEG and EMG power were normalized to the total power summed over all frequencies from 0 Hz to 500 Hz. This was an estimation of the power proportion contributed by a given frequency band.

2.4.6 Statistics

To evaluate our hypotheses, a two-step statistical analysis procedure was performed. The statistical analysis of the first step was performed between tasks RF-L0, RF-L5 and RF-L50. The data from 17 subjects who finished both unimanual and bimanual tasks were used in the analysis to explore how contractions of left-hand muscles at different levels influence the corticomuscular coherence in right hand. Thus, repeated-measures ANOVA was used to determine whether significant changes

occurred in the exerted force with right hand, the EMG activities of the rFDI muscle, the mean beta-band IM1-rFDI CMC and the normalized beta-band power of EEG and EMG signals. In the second step, the statistical analysis was performed between tasks RF-L5, R-L5, RF-L50 and R-L50 using all 22 subjects. A two-factor within-subject repeated measures ANOVA was used to determine the effect of contraction levels (5% and 50% of MVC) of left-hand muscles and the visual feedback for right hand on the exerted force with right hand, EMG activities of the rFDI muscle, the mean beta-band IM1-rFDI CMC and the mean normalized beta-band power of EEG and EMG signals. Post hoc test was performed on significant comparisons. In the following, the results for post hoc test were all corrected by the Holm-Bonferroni method. Group data are presented as mean \pm standard error.

3. Results

3.1 Preliminary results

3.1.1 Behavioral performance

The average behavioral performance of a typical subject is illustrated in Figure 2. The time courses of forces were averaged across all trials for each task [Figure 2 (a)]. Trials started at $t = 0$ s and lasted for 6 s. The forces of the left hand during the steady-hold periods of tasks RF-L50 and R-L50 were approximately 10 times those of tasks RF-L5 and R-L5. The average EMG activities of both hands for each task are shown in Figure 2 (b). In correspondence with the force data, EMG activities of the rFDI muscle changed minimally for different tasks, while EMG activities of the lFDI muscle increased notably during tasks RF-L50 and R-L50 compared with those

during tasks RF-L5 and R-L5.

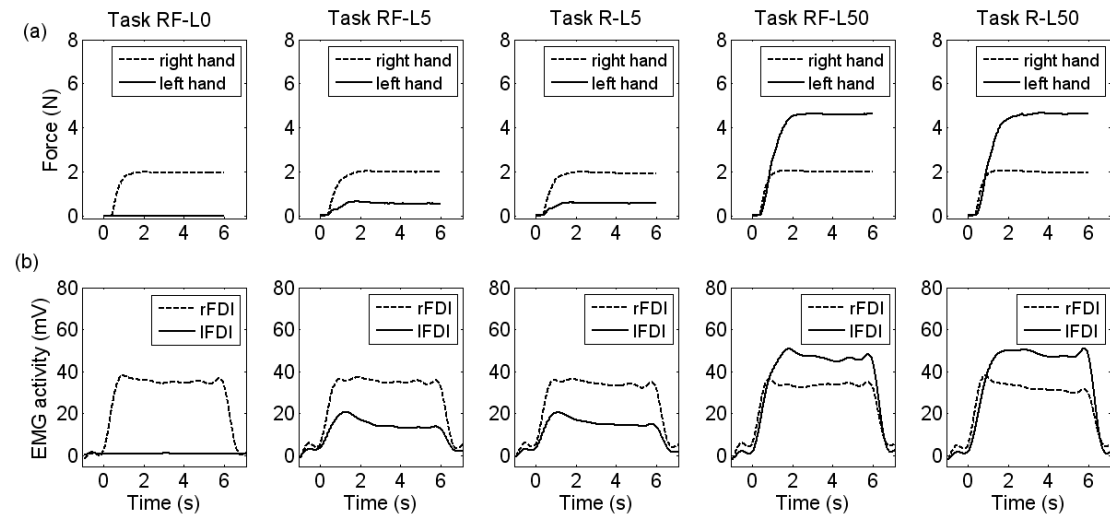


Figure 2. Average time courses of behavioral data for each task from a typical subject. Trials started at $t = 0$ s and ended at $t = 6$ s. (a) The exerted force of both hands was averaged across all trials for each task. Only force data within trials are shown here because inter-trial force data were not recorded. The target force for the right hand was 2 N for all tasks. By contrast, the target force for the left hand was 5% of MVC during tasks RF-L5 and R-L5 and 50% of MVC during tasks RF-L50 and R-L50. (b) The EMG activities of rFDI and IFDI muscles were averaged across all trials for each task. Corresponding to the time courses of exerted forces, the EMG activities of the rFDI muscle were almost equal among different tasks. By contrast, the EMG activities of the IFDI muscle during tasks RF-L50 and R-L50 were much larger than those during tasks RF-L5 and R-L5.

3.1.2 Corticomuscular coherence and power of EEG and EMG

The Z-score CMC topographies over the 15-30 Hz frequency band were averaged across all subjects for each muscle and each task (Figure 3). The average results showed that the strongest corticomuscular coherence emerged at the contralateral primary motor area to the muscle.

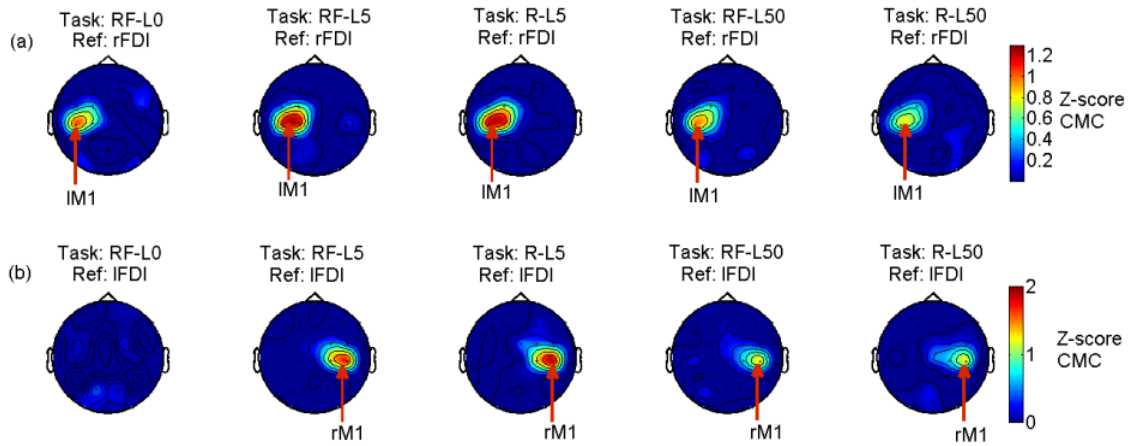


Figure 3. Topographies of average Z-score CMC over the 15-30 Hz frequency band across all subjects for each task and each muscle. (a) The strongest beta-band corticomuscular coherence between the electrical activities of the scalp and the rFDI muscle emerged at the left primary motor area (IM1). (b) The strongest beta-band corticomuscular coherence between the electrical activities of the scalp and the lFDI muscle emerged at the right primary motor area (rM1).

Time-frequency analysis was used to determine how the CMC spectrum and the power of EEG and EMG signals changed over time. The time-frequency plots of the CMC spectrum and normalized EEG and EMG power of a typical subject are illustrated in Figure 4. These plots were obtained by averaging the results of time-frequency analysis across all bimanual tasks. EEG power was mainly within the band less than 12 Hz. An event-related desynchronization emerged at approximately 10 Hz at both left and right primary motor areas. The EMG power spectrum of the rFDI muscle differed from that of the lFDI muscle. From the CMC spectrum, the strongest coherence emerged within the beta band (i.e. from 15 Hz to 30 Hz) and during the steady-hold period. Note that the beta-band IM1-rFDI CMC decreased during the later steady-hold period and the rM1-lFDI CMC also emerged in the gamma band >30 Hz.

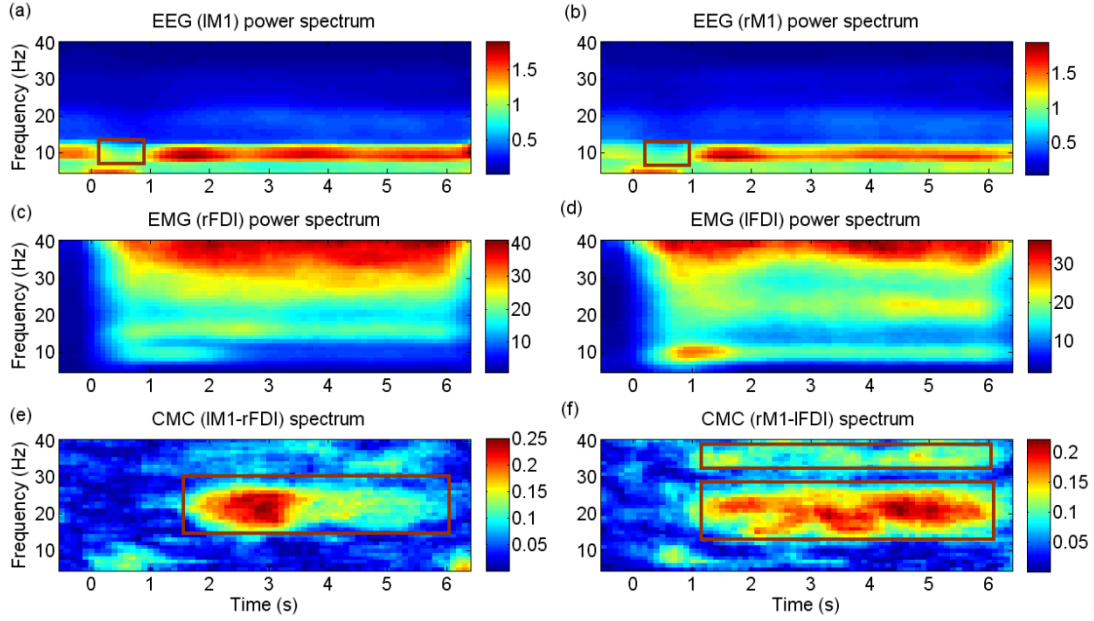


Figure 4. Time-frequency plots of the EEG and EMG power and the CMC averaged across all bimanual tasks from a typical subject. Trials started at $t = 0$ s and ended at $t = 6$ s. (a), (b) Time-frequency plots of EEG power from the lM1 and rM1 areas respectively. An event-related desynchronization (marked with brown boxes) at 10 Hz was obtained immediately after the onset of trials at both primary motor areas. (c), (d) Time-frequency plots of EMG power from muscle rFDI and lFDI respectively. (e), (f) Time-frequency plots of the lM1-rFDI and rM1-lFDI CMC respectively. During the steady-hold period, the strongest corticomuscular coherence (marked with brown boxes) emerged within the beta band and during the later steady-hold period, the lM1-rFDI CMC decreased. The rM1-lFDI CMC also showed in the gamma band (marked with the brown box).

3.2 Statistical analysis

3.2.1 Behavioral performance

The purpose of statistical analysis for behavioral performances was to verify whether different task conditions had significant influence on right-hand muscle

activities. The mean precision grip force was 1.97 ± 0.01 N for task RF-L0, 1.98 ± 0.01 N for task RF-L5, 1.91 ± 0.02 N for task R-L5, 2.02 ± 0.01 N for task RF-L50 and 2.01 ± 0.02 N for task R-L50. In the first-step statistical analysis, the results of ANOVA showed that the precision grip force differed between task RF-L0, RF-L5 and RF-L50 (F statistic, 10.57; df, 2; $p < 0.001$). Further post hoc test showed a significant increase in the precision grip force during task RF-L50 compared with that during task RF-L0 (T statistic, 3.46; df, 16; $p < 0.005$) and task RF-L5 (T statistic, 4.74; df, 16; $p < 0.0005$). No significant difference was found between task RF-L0 and RF-L5 (T statistic, 1.28; df, 16; $p > 0.1$). However, the results of ANOVA showed EMG activities of the rFDI muscle did not change significantly between task RF-L0, RF-L5 and RF-L50 (F statistic, 2.599; df, 2; $p > 0.05$). In the second-step statistical analysis, the ANOVA results showed that both the contraction level of left-hand muscles (F statistic, 46.18; df, 1; $p < 0.00001$) and the visual feedback for right hand (F statistic, 6.31; df, 1; $p < 0.05$) had significant influence on the precision grip forces **with interactions** (F statistic, 17.81; df, 1; $p < 0.0005$). Post hoc test showed that the precision grip force decreased significantly (T statistic, 3.89; df, 21; $p < 0.001$) during task R-L5 compared with that during task RF-L5, but the difference between tasks RF-L50 and R-L50 was insignificant (T statistic, 0.52; df, 21; $p > 0.5$). Meanwhile, the precision grip force increased significantly during task RF-L50 compared with task RF-L5 (T statistic, 5.47; df, 21; $p < 0.00005$) and during task R-L50 compared with task R-L5 (T statistic, 6.26; df, 21; $p < 0.00001$). However, the ANOVA results showed that the contraction level of left-hand muscles (F statistic, 0.02; df, 1; $p > 0.5$)

and the elimination of visual feedback for right hand (F statistic, 3.15; df, 1; $p > 0.05$) had no significant influence on EMG activities of the rFDI muscle.

3.2.2 Power of EEG and EMG

The statistical analysis of EEG and EMG power was used to determine whether significant differences occurred in the cortical and muscular oscillatory activities among different task conditions. The ANOVA results in the first step demonstrated that the involvement of contractions of the left-hand muscles, whether at 5% or 50% of MVC, had no significant influence on either the beta-band EEG power of the IM1 (F statistic, 1.99; df, 2; $p > 0.1$) area or the beta-band EMG power of the rFDI muscle (F statistic, 1.99; df, 2; $p > 0.1$).

In the second step of the statistical analysis, only the contraction level of left-hand muscles was found to significantly influence the beta-band EEG power of the rM1 area (F statistic, 7.52; df, 1; $p < 0.05$) and the IM1 area (F statistic, 4.75; df, 1; $p < 0.05$) from the ANOVA results [Figure 5(a) (b)]. On the contrary, the ANOVA showed that the beta-band EMG power of the rFDI (F statistic, 4.59; df, 1; $p < 0.05$) and lFDI (F statistic, 7.31; df, 1; $p < 0.05$) muscle was mainly influenced by the visual feedback for right hand [Figure 5 (c) (d)].

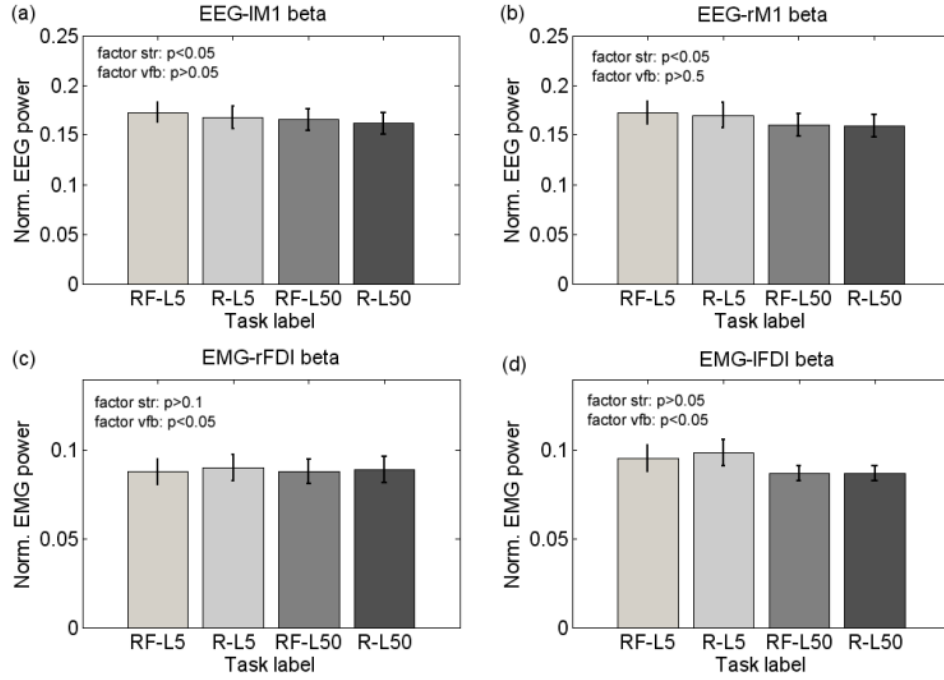


Figure 5. Average normalized beta-band EEG and EMG power across all the 22 subjects for four bimanual tasks. (a), (b) The mean normalized EEG power of some primary motor area was obtained by averaging the power of EEG signals from the electrodes of interest within that primary motor area across subjects. The electrodes of interest differed for different subjects. **str** – strength level of left hand; **vfb** - visual feedback for right hand.

3.2.3 Corticomuscular coherence

A similar two-step statistical analysis procedure was used to determine whether the corticomuscular coherence in right hand changed significantly in different motion conditions. In the first step of the statistical analysis, the Z-score IM1-rFDI CMC spectrum was averaged for tasks RF-L0, RF-L5 and RF-L50 across the 17 subjects who finished both unimanual and bimanual tasks [Figure 6(a)]. The ANOVA results showed that the mean Z-score IM1-rFDI CMC from three tasks were different (F statistic, 6.21; df, 2; $p < 0.01$). Further post hoc test demonstrated that the mean Z-score IM1-rFDI CMC increased significantly (T statistic, 2.76; df, 16; $p < 0.05$)

with a moderate contraction (5% of MVC) of left-hand muscles. However, as the contraction levels increased to 50% of MVC, the mean Z-score IM1-rFDI CMC decreased to almost equal to that of task RF-L0 (T statistic, 0.02; df, 16; $p > 0.5$). In addition, the difference between tasks RF-L5 and RF-L50 was significant (T statistic, 5.20; df, 16; $p < 0.0005$) [Figure 6(b)]. In the second step of the statistical analysis, the average Z-score IM1-rFDI CMC spectrum across all 22 subjects for four bimanual tasks is illustrated in Figure 6 (c). The ANOVA results showed that both the contraction level of left-hand muscles (F statistic, 34.53; df, 1; $p < 0.00001$) and the visual feedback for right hand (F statistic, 8.25; df, 1; $p < 0.01$) had a significant influence on the mean beta-band IM1-rFDI CMC with no interaction effect (F statistic, 2.70; df, 1; $p > 0.1$).

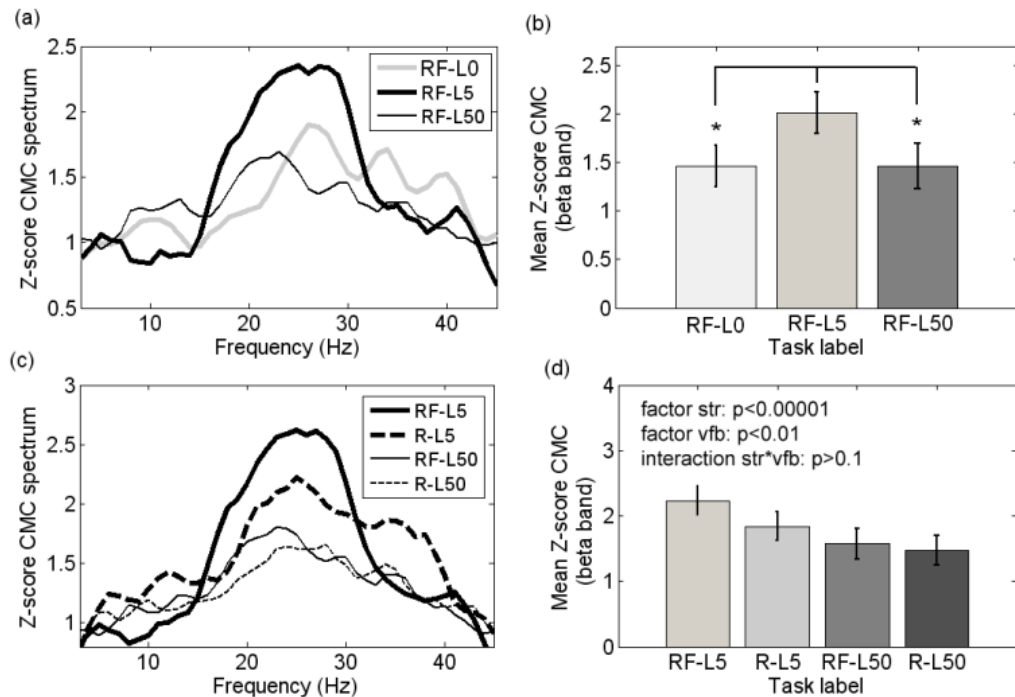


Figure 6. Average Z-score IM1-rFDI CMC spectrum and the results of statistical analysis. (a) The

Z-score IM1-rFDI CMC spectrum was averaged for tasks RF-L0, RF-L5 and RF-L50 across all 17

subjects who performed both unimanual and bimanual tasks. (b) The mean Z-score IM1-rFDI CMC in the beta band for tasks RF-L0, RF-L5 and RF-L50 was obtained and used for statistical analysis. (c) The Z-score IM1-rFDI CMC spectrum was averaged across all 22 subjects for four bimanual tasks. (d) The mean Z-score IM1-rFDI CMC in the beta band for four bimanual tasks was obtained and used for statistical analysis. * refers to $p < 0.05$ with Holm–Bonferroni correction for post hoc test. **str – strength level of left hand; vfb - visual feedback for right hand.**

In addition to exploring the corticomuscular coherence between IM1 areas and rFDI muscles, the corticomuscular coherence between rM1 areas and lFDI muscles was also statistically analyzed. A two-factor within-subject repeated measures ANOVA was used to test the influence of the contraction levels of left-hand muscles and the visual feedback for right hand on the mean beta-band and gamma-band (35 – 60 Hz) rM1-lFDI CMC. The Z-score rM1-lFDI CMC spectrum was averaged across all subjects [Figure 7 (a)]. The ANOVA results showed that only the contraction level of left hand muscles significantly influenced the mean Z-score rM1-lFDI CMC in both the beta band (F statistic, 11.94; df, 1; $p < 0.01$) and the gamma band (F statistic, 8.49; df, 1; $p < 0.01$). The elimination of visual feedback for right hand had no significant influence on the rM1-lFDI CMC in the beta-band (F statistic, 0.10; df, 1; $p > 0.5$) or gamma-band (F statistic, 0.37; df, 1; $p > 0.5$) range.

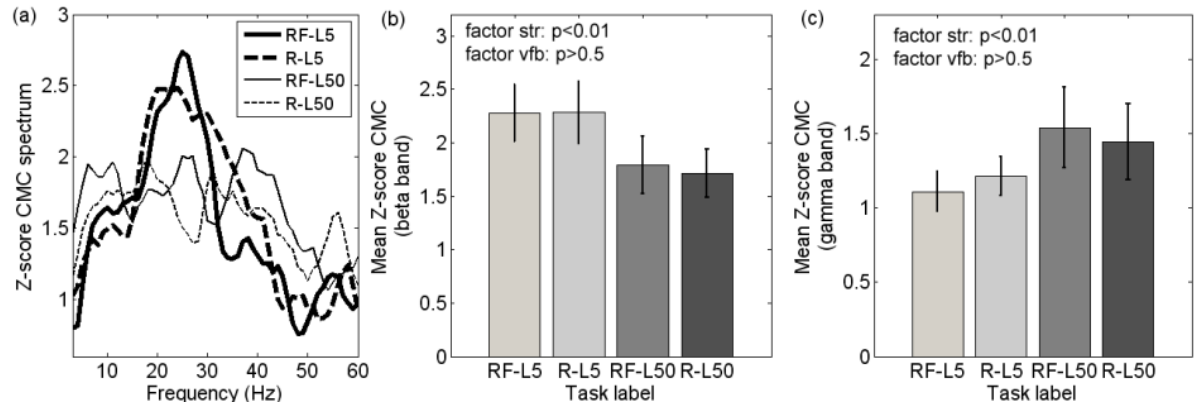


Figure 7. Average Z-score rM1-lFDI CMC spectrum and the results of statistical analysis. (a) The Z-score corticomuscular coherence spectrum was averaged across all 22 subjects for four bimanual tasks. The mean Z-score rM1-lFDI CMC in the beta band (b) and in the gamma band (c) for four bimanual tasks was obtained and used for statistical analysis. **str** – strength level of left hand; **vfb** - visual feedback for right hand.

4. Discussion

The present study aimed to verify how the voluntary contraction controlled by one hemisphere influences oscillatory processes and corticomuscular coupling of another voluntary contraction controlled by the other hemisphere. Results showed that the involvement of a moderate (5% of MVC) isometric contraction of left-hand muscles induced a significant increase in the corticomuscular coupling strength in right hand. Moreover, compared with moderate isometric contractions, strong isometric contractions (50% of MVC) of the left-hand muscles significantly decreased the beta-band corticomuscular coherence in right hand. The elimination of visual feedback for right hand significantly also decreased the corticomuscular coherence in right hand. The beta-band EEG power of both primary motor areas decreased significantly as the contraction level of left-hand muscles increased, which is

consistent with previous studies (Monica A. Perez, et al., 2012).

Although the forces exerted with right hand differed significantly during different tasks, it can be inferred that the changes in the LM1-rFDI CMC could not simply result from delicate force changes. Firstly, the differences among the forces were minor, such that they hardly induced any significant changes on EMG activities of the rFDI muscle. Secondly, opposite change tendencies of forces corresponded to the same change tendency of the LM1-rFDI CMC. The precision grip force with right hand increased along with the force level of left hand, whereas it decreased when the visual feedback for right hand was eliminated. However, both situations corresponded to a significant decrease of the beta-band LM1-rFDI CMC.

Perez et al. (Monica A. Perez, et al., 2012) found increased corticomuscular coherence in one hand along with the muscle contraction from the opposite hand. And they speculated that the enhanced corticomuscular coupling was due to the diffuse mirrored activity induced by the muscle contraction from the opposite hand. The mirrored activity increased the complexity of controlling a fine motion and then corticomuscular coupling needed for fine motor control was enhanced. On the contrary, Johnson et al. (Johnson, et al., 2011) revealed decreased corticomuscular coherence in one hand when muscle contraction from the opposite hand was involved. They speculated that the movement of one hand, like other types of simultaneous non-motor tasks, divided the attention from the motor control of the other hand, and thus decreased the corticomuscular coherence. This was supported by previous studies that demonstrated that the synchronous motor unit activity is greater during tasks that

require more attention (Schmied, Pagni, Sturm, & Vedel, 2000). The inference about the divided attention can also be supported by Kristeva-Feige's study (Kristeva-Feige, et al., 2002). In the current study, we found both changing tendencies of corticomuscular coherence in right hand along with different muscle contraction levels of left hand. According to these results, we inferred that both factors of divided attention and increased control complexity were involved simultaneously during bimanual motor tasks. Moreover, the degree of their effects may differ in different experimental conditions and either factor may play a dominant role. In the current study, when left hand performed a moderate muscle contraction, the corticomuscular coherence of right hand increased because divided attention induced by moderate muscle contraction was limited. In the meantime the control complexity of the right hand fine motion increased, which might be due to that the left hand muscle contractions brought perturbations of activity in the corticospinal tract to right hand. As the contraction strength of left-hand muscles increased further, the results showed the corticomuscular coherence in right hand decreased. The reason might be that the attention was divided seriously, even though strong contraction levels of left hand are more likely to affect the activity in the corticospinal tract to right hand (Hortobágyi, Taylor, Petersen, Russell, & Gandevia, 2003; Muellbacher, Facchini, Boroojerdi, & Hallett, 2000). That is to say, attention might play a dominant role that can influence the effect of control complexity, which could result in the change of corticomuscular coherence. When visual feedback was eliminated to further divide the attention on right hand, a significant decrease in the corticomuscular coherence in right hand was

observed as expected.

The finding that increased contraction levels of limb muscles decreased the corticomuscular coherence in the opposite hand was contrary to the results of Perez's study (Monica A. Perez, et al., 2012). A possible reason might be that Perez and her colleagues focused on the influence of contractions of the dominant hand muscles on the corticomuscular coherence in the non-dominant hand, a focus that was quite different from that of the current study. Performing a precision grip motion with the non-dominant hand may require more attention even though the dominant hand muscles contract at high levels, because the hemisphere contralateral to the non-dominant hand is believed to be specialized for detecting and responding to unexpected stimuli and the hemisphere ipsilateral to the non-dominant hand focuses in general on controlling well established patterns of behavior (Sainburg, 2014). Meanwhile, the control of strong contractions of dominant hand muscles may be easier than that of non-dominant hand muscles. Therefore, in Perez's study, corticomuscular coherence in the non-dominant hand would increase under the condition that attention was actually not significantly divided from the non-dominant hand.

The contradiction of the current study with Johnson's study (Johnson, et al., 2011) was that there was an increase tendency in right hand when left-hand muscles contracted at a moderate level. In Johnson's study, both hands performed the same motion and hand muscles contracted at the same level. Therefore, compared with the unimanual condition, the simultaneous motion of the other hand would divide

considerable attention. According to our speculation on the dominant role of attention, the corticomuscular coherence in the bimanual task would decrease compared with that in the unimanual task. This was quite different from the condition in the current study that the motor task of left hand was much easier than that of right hand. Therefore, divided attention from the control of right-hand muscle contractions was limited, which made the diffuse mirrored activity take effect and then resulted in an increase of corticomuscular coherence in right hand.

The control complexity for one hand may increase through a corticospinal tract with activity perturbations induced by muscle contractions of the opposite hand compared with a corticospinal tract at rest. The fact that muscle contractions of one hand can affect the activity of the corticospinal tract to the opposite hand may be based on the extensive connections between two sides of corticospinal tracts. For example, both sides of supplementary motor areas are connected to each other through the corpus callosum (Bear, Connors, & Paradiso, 2007) and interneurons connect the alpha motor neurons together that innervate limb muscles of both sides to generate the spinal motor programs (Bear, et al., 2007). An exemplary demonstration is that there is a default tendency to produce minimal mirror movements in one hand when subjects perform difficult or effortful movements using the opposite hand (Beaulé, Tremblay, & Théoret, 2012; Koerte, et al., 2010; Schm, Perez, Xu, Hidler, & Cohen, 2010). Interhemispheric inhibition (Welnarz, Dusart, Gallea, & Roze, 2015), which plays an important role to perform purely unimanual movements or tasks requiring independent actions with two hands, also demonstrate the ability that

activities of one corticospinal tract can affect the other corticospinal tract.

The corticomuscular coherence of left hand also showed task-dependent features. As the contraction level increased, the beta-band corticomuscular coherence in left hand decreased significantly, which is consistent with that in previous studies (Brown, Salenius, Rothwell, & Hari, 1998; Monica A. Perez, et al., 2012). Considering the concurrent decrease of EEG spectral power in the beta band at the right primary motor area, the decrease in corticomuscular coherence possibly resulted from the decrease in synchrony of the cortical motor network. Increased gamma-band corticomuscular coherence was found during strong contractions in the current study, consistent with the results of Brown's study (Brown, et al., 1998). A possible explanation is that the motor cortex becomes more excited during a stronger contraction of the contralateral hand, resulting in changes in the local network properties of the cortex from the beta- to the gamma-band oscillatory mode (Brown, et al., 1998). However, because the increase in gamma-band corticomuscular coherence is not a consistent result according to previous studies, additional studies are needed to verify whether the decrease in beta band and increase in gamma band are reflections of different underlying mechanisms.

The corticomuscular coupling of activities between the primary motor area and the contralateral contraction muscle is weakened for post-stroke patients (Fang, et al., 2009; T Mima, et al., 2001). Previous studies demonstrated that higher corticomuscular coherence was related to improved fine movement controls (Kristeva, et al., 2007; Mendez-Balbuena, et al., 2012), and motor learning was associated with

increased corticomuscular coherence and better performances (Mendez-Balbuena, et al., 2012). Thus, it may be speculated that corticomuscular coherence is possibly an underlying mechanism for fine movement controls, and motor deficits may be a consequence of weakened corticomuscular coupling. From this point of view, increasing the corticomuscular coherence of the affected limb for stroke patients is either the way or the goal for regaining motor function. The possible clinical implication of the current study is that the bimanual training should be used with caution for stroke patients. The involvement of movements with the unaffected hand may enhance the coupling strength between the damaged hemisphere and the affected hand. However, the difficulty of tasks for the unaffected hand must be controlled carefully to avoid too much attention being divided from the affected hand.

In summary, this study found that muscle contractions with one hand can influence the corticomuscular coherence in the opposite hand in a complex manner. Moderate muscle contractions or easy motor tasks of one hand may increase the corticomuscular coherence in the opposite hand. And strong muscle contractions may result in decreased corticomuscular coherence compare with moderate muscle contractions. We speculated that increased complexity and divided attention can influence the corticomuscular coherence during bimanual tasks and the attention to motor control is assumed to play the dominant role.

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