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Multiple interactions between hemispheres of the brain modulating coupling of bilateral movements

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Abstract—**Interaction between motor areas of the right and left hemispheres of the brain is important for generating bilateral coordinated movements. We investigated how bilateral coupling, which results from the interhemispheric interaction, is modulated during coordinated movements. We tried to estimate coupling and stability of bilateral movements during continuous movements of the right and left index fingers. The experimental results show that bilateral coupling strengthens during symmetric movements and same directional movements. However, coordination stabilities depend on only symmetry. The results suggest that two or more interhemispheric interactions contribute to control the bilateral coordinated movements.**

I. INTRODUCTION

The central nervous system has many areas for motor control, for example, primary, premotor, and supplementary motor areas. These cortical motor areas are important for controlling the movements of contralateral body parts. When we control the right and left body parts simultaneously, the bilateral hemispheres work cooperatively. The right and left hemispheres of the brain have connections throughout the corpus callosum and these connections generate the interaction between the hands during bilateral coordinated movements [1].

In addition, many previous studies suggested that characteristic of bilateral movement changes depending on how the right and left body parts are moved. During bilateral finger movements, symmetric movements are more stable than asymmetric movements. If the cycling frequency of asymmetric movement increases, the movement shifts suddenly to symmetry. This phenomenon is called “phase transition”. On the contrary, the opposite transition does not occur [2]. Other studies reported that movement directions of bilateral body parts are also related to stability [3] [4] (We define the stability as “coordination stability” in this paper.). These results suggest that the bilateral interaction changes depending on the relative state between right and left movements, and the change of the interaction affects coordination stability.

On the other hand, several imaging studies reported that the sensorimotor and premotor areas’ activities opposite to the damaged side become stronger depending on recovery of motor function [5] [6]. These results suggest that the neural plasticity occurred to compensate for the function of contralateral motor area. That is, hemisphere obtains the state on the other side and then, according to the state (i.e. damage) of motor area in opposite side, the neural structure changes.

It can be interpreted that the interhemispheric interaction is important mechanism for the bilateral control and the recovery of motor function toward brain damage. In order to clear the information exchanged by the interaction, we investigated the modulation manner of the interhemispheric interaction during bilateral movements. Especially, we focus on symmetry (symmetric or asymmetric) and relative direction (same or opposite) between right and left body movements.

II. MATERIALS AND METHODS

A. *Experimental setup*

Figure 1 shows the experimental setup. Subjects were seated on an adjustable-height chair in front of a desk, and their heads were placed on a chin support to fix the head position. The subjects gripped handles attached to the desk with both their hands. The distance between the right and left hands was 15 cm. The subjects’ hands were occluded with a board. The positions of both index fingers were obtained with a motion capture system (ProReflex, Qualisys Co., Sweden) at 250Hz and the positions of both fingers were displayed on a monitor as finger cursors in real time, and the subjects had to control the finger cursors. There were two targets for each finger cursor and the distance between these targets was 10 cm. When the index finger moved 2.5 cm, the finger cursor moved 10 cm on the monitor.

When the task started, the desired cursors appeared. The desired cursors made reciprocal motion between the targets with a constant movement frequency (0.5 Hz). We asked the subjects to continuously perform flexion and extension movements at 0.5 Hz and also asked them to match the finger cursors to the desired cursors. One session consisted of eight cycles.

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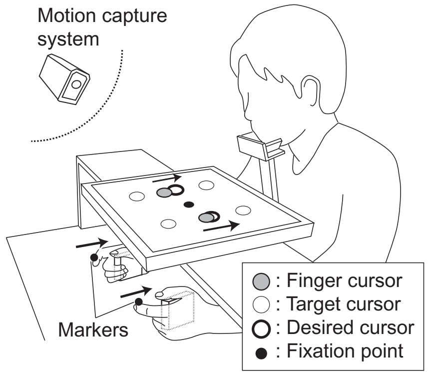

Fig. 1. Experimental setup.

B. Finger cursor's gain

The subjects started moving their fingers bilaterally with a 2.5-cm amplitude. After the 5th cycle, the left finger cursor disappeared from the monitor and the right finger cursor gain was changed. That is, the desired amplitude of the right finger changed. The subjects needed to modify their right finger amplitude in the latter half of each session. On the other hand, the subjects were asked to keep the same amplitude of their left fingers throughout a session (2.5 cm).

C. Task conditions

We set four conditions in a 2 × 2 factorial design (Fig. 2). There were two postures and the subjects performed a movement in which homologous muscles were engaged simultaneously (symmetric movement) and a movement in which homologous muscles were engaged alternately (asymmetric movement) in each posture. All target cursors were displayed at the same distance from the fixation point at the center of monitor. In conditions 2 and 3, the target cursors of the right finger were placed at the top of the monitor and those of left finger were placed at the bottom.

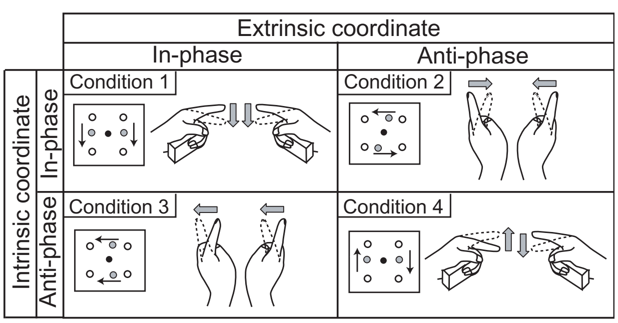

Fig. 2. Task conditions defined by intrinsic and extrinsic coordinate frames.

Since symmetry can be represented in muscle space, we defined symmetric movements as intrinsic in-phase movements (conditions 1 and 2). Similarly, movement direction can be represented in external space, and we defined the same directional movements as extrinsic in-phase movements (conditions 1 and 3).

The order of conditions the subjects performed was conditions 1-2-3-4-4-3-2-1. The subjects repeated five times in each condition. Thirteen right-handed healthy subjects (aged 19-38, mean 27.5 years) participated in our experiment.

D. Data analysis

When the subjects modified the amplitude of their right fingers, the amplitude of their left finger changed involuntarily (Fig. 3). We defined the left finger's response according to modification of right finger movements as bilateral coupling. The stronger the bilateral coupling, the stronger the response of the left finger will be. Bilateral coupling was then calculated as $L(c)/R(c)$ (c: cycle number). $L(c)$ and $R(c)$ are the amplitude variations after the 5th cycle.

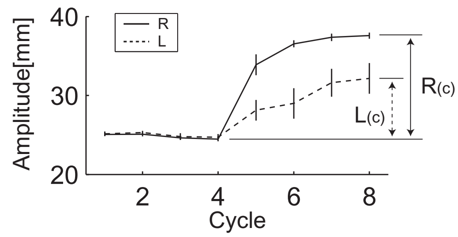

Fig. 3. Amplitude transitions of right and left fingers.

In addition, we estimated coordination stability. The relative phase between both index fingers was calculated using Equation (1), adapted from Kelso et al. [7].

$$\phi = \theta_L - \theta_R = \tan^{-1}\left[\frac{(dX_L/dt)}{X_L}\right] - \tan^{-1}\left[\frac{(dX_R/dt)}{X_R}\right], \quad (1)$$

where X is the position of the index finger after rescaling the interval [-1 1] for each cycle, and dX/dt is the normalized instantaneous velocity. The coordination stability is defied as the standard deviation of the relative phase.

III. RESULTS

A. Bilateral coupling

Figure 4A shows bilateral couplings. In each condition, a 1-way analysis of variance (ANOVA) was carried out on the results of bilateral couplings from the 5th to 8th cycles. In condition 3, the analysis revealed a statistically significant main effect, and the results of condition 2 had the same trend as condition 3. That is, the time constants of conditions 2 and 3 were larger than that of condition 1 (condition 1: $F(3,36) = 1.12$, $p = 0.35$, condition 2: $F(3,36) = 2.25$, $p < 0.1$, condition 3: $F(3,36) = 3.70$, $p < 0.05$, condition 4: $F(3,36) = 1.47$, $p = 0.24$). This means that the left finger movements in conditions 2 and 3 were affected slowly compared to those in condition 1.

Furthermore, a 2-way (intrinsic × extrinsic) ANOVA was carried out on bilateral couplings in each cycle (Fig. 4B: 5th cycle, Fig. 4C: 8th cycle). This analysis revealed a statistically significant main effect for intrinsic coordinate and extrinsic coordinate and these interactions in most cycles (Table I). In

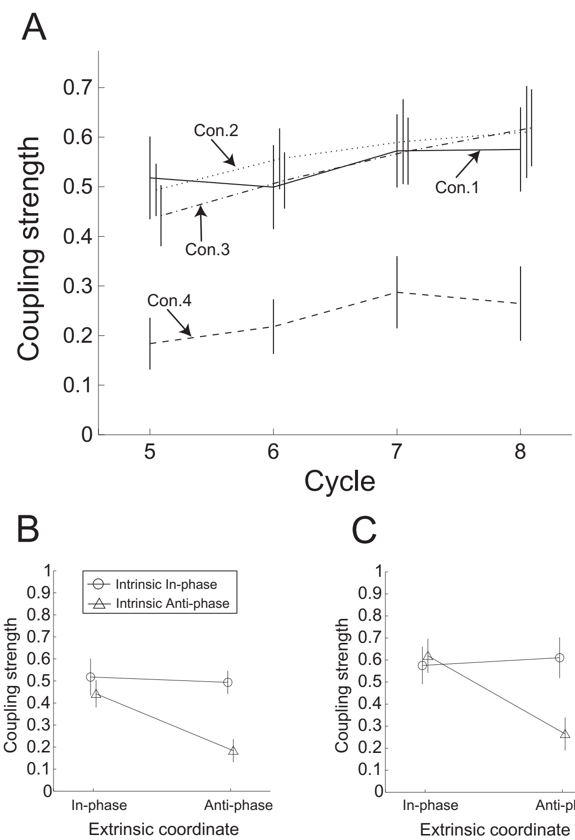

Fig. 4. A: Bilateral coupling of four conditions (5^{th} – 8^{th} cycle).
B: 5^{th} cycle, C: 8^{th} cycle

TABLE I
F VALUES AND LEVEL OF SIGNIFICANCE OF 2-WAY ANOVA ON BILATERAL COUPLINGS IN EACH CYCLE.
$F(df_1,df_2) = F(1,12)$, $*p < 0.05$, $**p < 0.01$

Cycle	5^{th}	6^{th}	7^{th}	8^{th}
Intrinsic	26.38**	12.62**	19.57**	12.56**
Extrinsic	14.01*	11.19**	13.11**	13.10**
Interaction	3.86	11.17**	8.55*	8.16*

addition, coupling in condition 4 was significantly smaller than that in the other conditions.

B. Coordination stability

Figure 5 shows the coordination stabilities. We divided a session into two parts, pre-phase (Fig. 5A: 1^{st} - 4^{th} cycles) and post-phase (Fig. 5B: 5^{th} - 8^{th} cycles), and calculated the coordination stability in each phase. A 2-way (intrinsic * extrinsic) ANOVA was carried out on the coordination stabilities in pre- and post-phases. The analysis revealed a statistically significant main effect only for the intrinsic coordinate (Table II).

IV. DISCUSSION

Left finger movements were strongly affected except in condition 4. These results indicate that the right and left motor systems were strongly coupled. According to previous studies, ipsilateral innervations of the left primary motor cortex are more prominent than that of the right primary motor cortex [8] [9]. In addition, the left primary motor cortex inhibits the right primary motor cortex more effectively than vice versa [10] and also during symmetric bilateral movements, there is asymmetric activation between the right and left primary motor cortexes [11]. These findings suggest that motor commands could be shared between bilateral motor systems because homologous muscles activate at the same time during symmetric movements. As a result from sharing motor commands, the variability between bilateral movements decreases. In conditions 1 and 2, the subjects performed symmetric movements with strong coupling and high stability. Our results of these conditions are consistent with the shared motor command hypothesis.

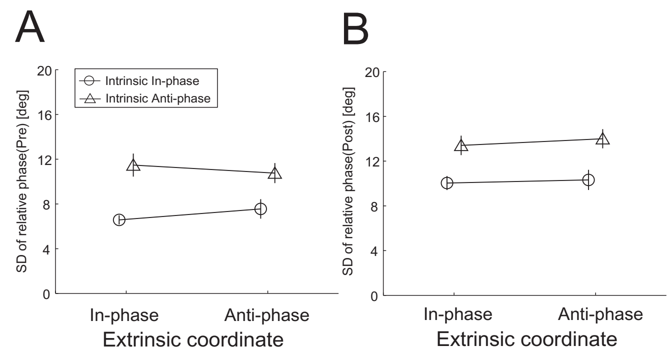

Fig. 5. Coordination stability.
A: Pre-phase, B: Post-phase.

TABLE II
F VALUE AND LEVEL OF SIGNIFICANCE OF 2-WAY ANOVA ON COORDINATION STABILITIES IN EACH PHASE.
$F(df_1,df_2) = F(1,12)$, $**p < 0.01$

Phase	Pre	Post
Intrinsic	21.71**	42.45**
Extrinsic	0.005	0.34
Interaction	1.02	0.01

Although strong coupling was observed in condition 3, bilateral movements were not stable. In addition, since the both fingers moved asymmetrically, motor commands could not be shared. It is suggested that when the brain tries to output the same directional movements, bilateral coupling is generated by a different mechanism from the mechanism supported in previous studies. It is possible that higher motor areas, such as premotor, are related to bilateral coupling during the same directional movements. Kakei et al. reported that there are two types of neurons in the primary motor cortex. For the first type, neural activity depends on intrinsic information (muscular activity). For the second type, neural activity depends on extrinsic information (movement direction) [12]. On the other hand, almost all of the neural activities in the ventral premotor cortex depend on extrinsic information [13]. According to these results, it could be said that bilateral coupling during the same directional movement is generated by the sharing of "motor planning" between the premotor cortexes. That is, bilateral control systems have multiple interhemispheric interactions at different levels.

Our findings will give the idea for more effective neuromuscular rehabilitation task. It is widely thought that the mirror movements are effective task as one of the rehabilitation techniques. For example, hemiplegic patients perform bilateral movements as part of their rehabilitation; this training is called "mirror therapy" [14]. In this rehabilitation technique, the intrinsic coordination between homologous muscles would encourage the recovery of motor function. On the other hand, our results suggest that extrinsic interaction between bilateral higher motor areas occur by performing the same directional movements. Mechsner et al. [15] claimed that perceptual process can modulate coordinated control systems. Therefore, if we use the visual feedback in the rehabilitation tasks appropriately, we can construct not only intrinsic coordination but also extrinsic coordination as the multiple interhemispheric interactions during bilateral movement. That is, we could set more effective neuromuscular rehabilitation task by facilitating the interactions in the lower level (primary motor cortex) and the higher level (premotor cortex).

In the future, we plan to identify the brain areas which have the intrinsic interaction (movement symmetry) and the brain areas which have the extrinsic information (movement direction) during bilateral movements using functional magnetic resonance imaging (fMRI). Some previous studies suggest supplementary motor and premotor areas contribute to controlling bilateral movements, and the supplementary motor area, especially, modulates interhemispheric interactions depending on symmetry [16] [17]. However, it is not clear what information the premotor processes for controlling bilateral movements. We will attempt to investigate the bilateral coordinated control mechanism included higher motor areas.

V. CONCLUSIONS

We investigated interhemispheric coupling by conducting bilateral movement tasks. Our results suggest that multiple interactions based on intrinsic coordinate (symmetry) and extrinsic coordinate (movement direction) relate to control coordinated movements. In addition, it can be presumed that several motor areas have interhemispheric interactions to obtain the information of contralateral state during bilateral movements.

In the future, we plan to clarify the brain areas which are related to intrinsic and extrinsic interactions using imaging techniques. If we can identify these brain areas, the findings would further contribute to neuromuscular rehabilitation.

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