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Planning of Bimanual Movement Training Based on the Bilateral Transfer of Force and Proprioception by Using Virtual Impairment

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Abstract

Bilateral movement training based on robot-aided rehabilitation systems has been attracting a lot of attention as a post-stroke motor rehabilitation protocol. However, the critical training parameters that underlie the efficiency of bilateral movement have not been clarified. The primary question for planning of bilateral movement training is how the upper extremities interact with each other when function in one of the limbs is less than normal one. The effects of different conditions which were imposed on the unimpaired upper extremity were investigated to find exact therapeutic conditions for planning more appropriate bilateral movement training. Active/passive, loaded/non-loaded, and unimanual/bimanual movements were used as the experimental conditions. Twenty subjects were randomly assigned to one of four groups, namely the passive group (PG), the active non-load group (ANLG), active load group (ALG), and the control group (CG) and were asked to perform tasks with their left upper extremity with respect to the conditions. To carry out the experiments with healthy subjects, we use a robotic force field paradigm to impose a virtual impairment on the right upper extremity of the all subjects. After subject adapted to the robotic force field, all subject conducted the aftereffect test which consist of a bimanual movement task while the CG performed a unimanul movement task. Here we assume that, based on the bilateral transfer aspect, the recovery time from the adaptation to the robotic force field is varied by the conditions of left upper extremity in bimanual movement task. By comparing the recovery time from adaptation in each condition, we found the exact condition for planning of effective bilateral movement training. The comparison results revealed that the active loaded group showed the recovery time from adaptation was faster than another groups.

Keywords: Proprioception; Bilateral transfer; Bimanual movement training; Active/passive; Handedness; Virtual impairment

Introduction

Robot-aided rehabilitation systems based on the application of robot technology [1] have been attracting a lot of attention to support the rehabilitation training since one-on-one manual therapy has several limitations; it is labor-intensive, time consuming, and lacks exact repeatability. In robot-aided rehabilitation therapy, the duration and the number of training sessions can be increased without increasing the burden on physiotherapists. Furthermore, robot-aided rehabilitation systems provide quantitative measurement to support observation and evaluation of the rehabilitation protocol [2]. Because post-stroke hemiparesis, paralysis of one side of body, is one of the most common conditions, many robot-aided rehabilitation systems for upper extremities have been developed to support training that focuses on paretic upper extremities [3]. However, many activities of daily living such as driving a car, and opening the lid of jar naturally require the coordinated participation of both hands and sound neurological interlimb coordination postulates in activating motor synergies between limbs [4]. This provides a rationale for the incorporation of bilateral movement training into upper extremities rehabilitation protocols [5]. Additionally, clinical evidence from fMRI and TMS based studies of neural plasticity [6] and brain activation [7,8] supports the benefits of bilateral movement training [9]. Although various types of bilateral movement training have been proposed to improve the functioning of the hemiplegic limb [10-12], the critical training parameters that underlie the efficiency of bilateral movement have not been clarified [5]. For example, cortico-motor facilitation under synchronous conditions was reported to be similar to facilitation under asynchronous conditions in Stinear and Byblow [13]. For the asynchronous condition, a phase shift of 60 degrees was imposed upon the movements of the contra-lateral upper limb.

The primary question for planning of bilateral movement training is how the upper extremities interact with each other when function in one of the limbs is less than normal one. The bilateral transfer, transfer of a skill and sensory or motor information on one side of the body to the other side, is considered as one kind of the interactions between upper extremities and the conditions actively causing the bilateral transfer will induce the neural plasticity for the recovery and reorganization of lost motor function. Thus, investigation on conditions which cause a strong positive bilateral transfer can provide insight into planning of more appropriate bilateral movement training. The majority of investigations of bilateral transfer are mainly conducted the transfer direction, the effect of handedness and bilateral transfer of learning; from right to left side of the body or vice versa, laterality and sensory or motor information [14]. Criscimagna-Hemminger et al. [15] reported the transfer direction of learned dynamics for reaching movements in right-handed subjects. The results suggest that the learning with dominant arm could be represented in the left hemisphere with neural elements tuned to both the right arm and the left arm. On the contrary, learning with the nondominant arm seems to rely on the elements in the nondominant hemisphere tuned only to movements of that arm. However, the research results which investigated the exact therapeutic

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conditions such as active/passive movement relate to activities of the bilateral transfer have so far been insufficient.

Most of the developed robot-aided rehabilitation systems which support the bilateral movement training provide the bimanual symmetric motions, which are the most common bimanual training mode, through measuring the position of the normal upper limb and mirroring the motion to the impaired limb using robot manipulator or exoskeleton type robotic devices [16-18]. However, robot-aided rehabilitation systems have the clear benefit of allowing for the free construction of various bilateral movement trainings which induce much more interactions between normal and paretic upper extremities. In the robot-aided rehabilitation systems which support the bilateral movement trainings, thus, it is important to find the exact therapeutic conditions that would cause much more interaction between upper extremities in order to plan effective bilateral movement training.

The bilateral transfer of sensory information is one kind of the interaction between upper extremities. The neural plasticity of the brain for the recovery and reorganization of lost motor function will be much more induced by actively causing bilateral transfer. However, the research results which investigated the effects of the conditions such as active/passive movement relate to activities of the bilateral transfer have so far been insufficient. Thus, in our previous researches [19,20], to find the exact conditions that would actively cause the bilateral transfer, we have discussed the bilateral transfer in sensory system, especially proprioception and force perception. The proprioception plays an important role for goal-directed movements which consists of the most common physical therapy. According to the result of study for the proprioception [19], the bilateral transfer of proprioception actively caused when the proprioceptive sensory feedback was acquired from the active movements; the subject controlled the robot end-effector through their voluntary movements. In the passive movement, the subject was guided by the robot movement for the goal-directing trajectory. Based on this result, to verify the effect of voluntary motor function, active and passive conditions were used in this study.

In the robot-aided rehabilitation training, robots commonly resist the movements of upper extremity or compensate the force of gravity of the upper extremity itself. Therefore, force perception is also important which should be considered. The result of the study for force perception [20] indicated that the bilateral transfer of force perception was the function of the size of force, thus bilateral transfer was more actively occurred in loaded conditions. According to this aspect of the bilateral transfer of force perception, we used loaded and non-loaded conditions for the comparison.

The objective of this research is the investigation of the effect of different conditions which are imposed on the unimpaired upper extremity for planning more appropriate bilateral movement training. In this research, active/passive, loaded/non-loaded, and unimanual/bimanual movements were used as the experimental conditions. Twenty subjects were randomly assigned to one of four groups, namely the passive group (PG), the active non-load group (ANLG), active load group (ALG), and the control group (CG) and were asked to perform tasks with their left upper extremity with respect to the conditions. To carry out the experiments with healthy subjects, we use a robotic force field paradigm, a property of motor adaptation to the robotic force field, to impose a virtual impairment on the right upper extremity of the all subjects. After subject adapted to the robotic force field, to investigate the effects of each condition, all subject conducted the aftereffect test which consist of a bimanual movement task while the CG performed a unimanul movement task. We purpose that, based on the bilateral transfer aspect, the recovery time from the adaptation to the robotic force field is varied by the conditions of left upper extremity in bimanual movement task. Thus the recovery time during bilateral movement task was used as an evaluation variable to investigate the effect of different conditions. By comparing the recovery time from adaptation in each condition, we found the exact condition for planning of effective bilateral movement training. The comparison results revealed that the active loaded group showed the recovery time from adaptation was faster than another groups. We found that, for more effective bilateral training, robot-aided system supports the bilateral movement should set the active movements with resistive force condition for unimpaired upper extremity.

Methods

Force field paradigm

Recently, robotic force field paradigm in which robot creates a novel dynamic environment has been used to investigate the human ability to adapt dynamic force field. The robotic systems enable us to simulate various experimental environments by creating a wide range of force fields in an arbitrary direction, and measuring the reaction force and movements generated by the human [21]. In the typical study [22], a two degrees-of-freedom robotic device generated perturbing force field, in which the forces depended on the hand velocity, to the hand of subjects who reached to the target position with straight line path in a horizontal plane. The path of hand was curved by the force field in the initial stage. After the adaptation to the forces with practice, the subjects strengthened their hand path against the perturbing force in the final stage. After adaptation to the perturbation, when the forces were unexpectedly removed, the subjects exhibited aftereffect which displayed hand path in the opposite direction of the perturbing force along a mirror-symmetric path to the one observed during initial stage exposure. This aftereffect indicated that the internal model of the environment was created and the nervous system generates a prediction of the expected perturbing forces.

Based on the aftereffect, Scheidt et al. [23] investigated the persistence of motor adaptation by comparing kinematic and dynamic measures of performance when kinematic errors were allowed to occur after removal force fields(null field) in the horizontal plane, or prevented by a mechanical channel which enforce a straight-ling path on the movements. Hand forces recorded at the knob revealed that when kinematic errors were prevented from occurring by the application of the mechanical channel, subjects persisted in generating large forces that were unnecessary to generate an accurate reach. The magnitude of these forces decreased slowly over time, at a much slower rate than when subjects were allowed to make kinematic errors. This indicated that the recovery from adaptation to the novel field was much slower compared with when kinematic aftereffects were allowed to occur in the null field.

Virtual impairment

Emken et al. [24] used a robotic force field paradigm to impose a virtual impairment for a walking task on the unimpaired subjects to derive their robotic training algorithm. In their study, to create the virtual impairment, a force which was proportional to the forward velocity of the subject's ankle pushed the leg upward only during the swing phase of gait. Thus, the virtual impairment tended to make the subject step with an abnormally high step trajectory during swing.

In this study, a human ability to adapt robotic force field paradigm was used to impose a virtual impairment on the right upper extremity

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of healthy subjects; after the adaptation to the forces with practice, when the perturbing forces were removed, the subject exhibits aftereffect for a while. We focused on the property of persistence of motor adaptation which was investigated by Scheidt et al. [23] as mentioned in the previous phrase. When kinematic errors were prevented by a mechanical channel, the recovery of motor adaptation (i.e., persistence of motor adaptation) was much slower compared with when kinematic aftereffects were allowed to occur in the null field. We supposed that, through bilateral transfer of sensory information, the persistence of motor adaptation was varied by the conditions of one upper extremity in the bilateral movement. Based on this hypothesis, we investigated the effects of the conditions imposed to the left upper extremity to find the exact therapeutic conditions for effective bilateral movement training by comparing the persistence of adaptation of right upper extremity in each condition.

Although various studies have reported that bilateral transfer can occur in either direction [25,26], right-handed subjects demonstrated better results when the direction of transfer is from left (non-dominant) to the right (dominant) hand rather than opposite [27,28]. In our experiment, we followed these results and explored only the direction from the non-dominant (left) to the dominant (right) hand. Thus, we used a robotic force field paradigm to impose a virtual impairment on the right upper extremity of the all subjects. And we evaluated its persistence of motor adaptation in different conditions of left upper extremity for each group.

Subjects

Twenty healthy right-handed, 20-30 year old male subjects with no history of orthopedic or neurological disorders participated in this experiment. All subjects were naive to the purpose of the experiment, and provided informed consent. The handedness of the subjects was evaluated by the Edinburgh Handedness inventory, a measurement scale used to assess the dominance of a person's right or left hand in everyday activities [29]. The subjects were randomly assigned by the imposing conditions on the left upper extremity to one of four groups, namely, the passive group (PG), the active non-load group (ANLG), active load group (ALG), and the control group (CG). Since muscle strength of each subject is different, the MVC (Maximum Voluntary Contraction) of each subject was measured so that the subject experienced a peak deflecting force depending on the muscle strength. In order to verify no differences among the groups in the MVC, we conducted the Kruskal-Wallis test for 4 independent samples test using the SPSS (SPSS Japan Inc.). The result indicated that there were no significant differences among the groups ($p>0.05$, approximate significance probability: 0.888).

Experimental apparatus

In this study, the experimental apparatus consists of two serial manipulators with 6 degrees of freedom and 6-axis force/torque sensors (NITTA Corporation) which were attached between the robot end-effector and the knob. The monitor is set 1.5 meters in front of the subjects who sit on the chair. The motions of manipulator are restricted on the horizontal plane (xy plane in Figure 1). The positions with respect to x and y of the end-effecter are defined as the output of the second-order dynamical system described by Eq. (1), i.e. impedance control. This equation is well-established in the field of robotics and human robot interaction [30].

$$F = M\ddot{z} + D\dot{z} + Kz \qquad (1)$$

The position x and y were calculated based on the (1), z was the dependent variables for calculating x and y. F was the force measured via the 6-axis force/torque sensor with sampling frequency of 50Hz; thus, x-axis force was used in (1) for calculating the x position, and y position was obtained by substituting y-axis force into (1). Therefore, the robot end-effetor was moved on the x-y plane by the subject's exerted forces which mean voluntary movement to the 6-axis force/torque sensor. In this way, the backdrivability requirement, which is the most important technical requirement for robotic force field paradigm, could be satisfied. The inertia (M), viscosity (D) and stiffness (K) are set

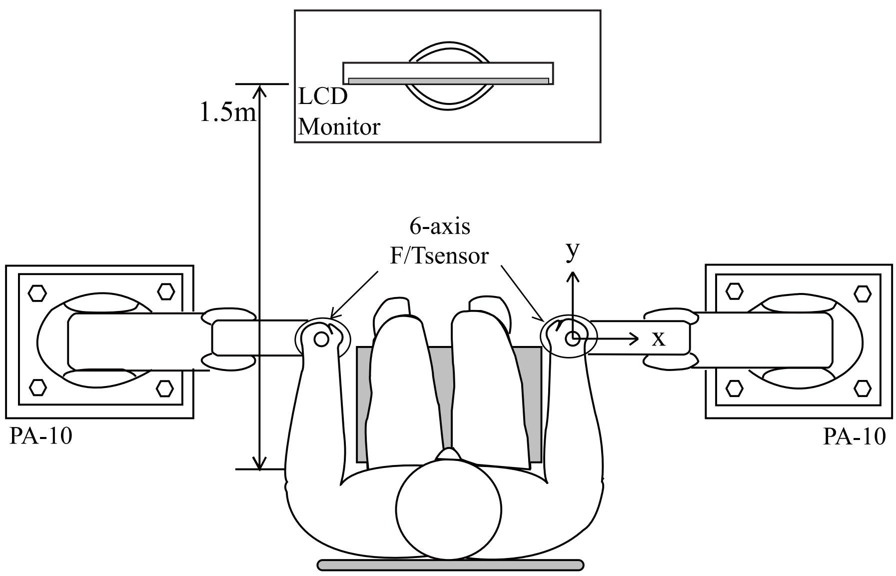

Figure 1: Top view of experimental setup.

to 0.1[kg], 10[N/ms] and 0[N/m] respectively. We chose these values, based on the results of preliminary experiments, so that the subject may move the robot end-effector with sufficiently small muscle force.

In this study, two different mechanical environments were presented to the all subjects: a Perpendicular Field and a Mechanical Channel Field. During the force field adaptation phase of the experiment, the subjects experienced the perpendicular field generated by the robot manipulator as a force at the hand ($[F_x, F_y]^T$), which was proportional to the velocity of the hand ($[v_x, v_y]^T$).

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} 0 & -P \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \end{bmatrix} \tag{2}$$

Here, the perturbing force, $[F_x, F_y]^T$, is given in Newtons (N) and the velocity, $[v_x, v_y]^T$, is in meters per second (m/s). The viscous field was generated to deflect the hand perpendicularly from its intended path with a force proportional to hand velocity along its path. Since the subjects have different muscle force, to avoid individual difference, the P determined the size of perturbing force $[F_x, F_y]^T$ was proportional to the Maximum Voluntary Contraction of each subject. Thus, a subject performing the movement in the allotted time could experience a peak deflecting force defined by the P.

During the channel phases of the experiment the subjects moved in the guided straight-line path connecting the start point and target point. The mechanical channel field was implemented by the constraint motions of manipulator were restricted on the y-axis in the Figure 1. Thus, the calculating the x position with the (1) was excluded during the channel phases. Here, since the subjects could move at any speed and with sufficiently small muscle force, the mechanical channel field constrained the hand path not movement timing. The overall effect of the channel was to minimize the kinematic consequence of any off-direction (perpendicular) force exerted by the subject, thus, the persistence of adaptation decreased much slower rate than when subjects were allowed to make kinematic errors like the primary result of Scheidt et al. [23].

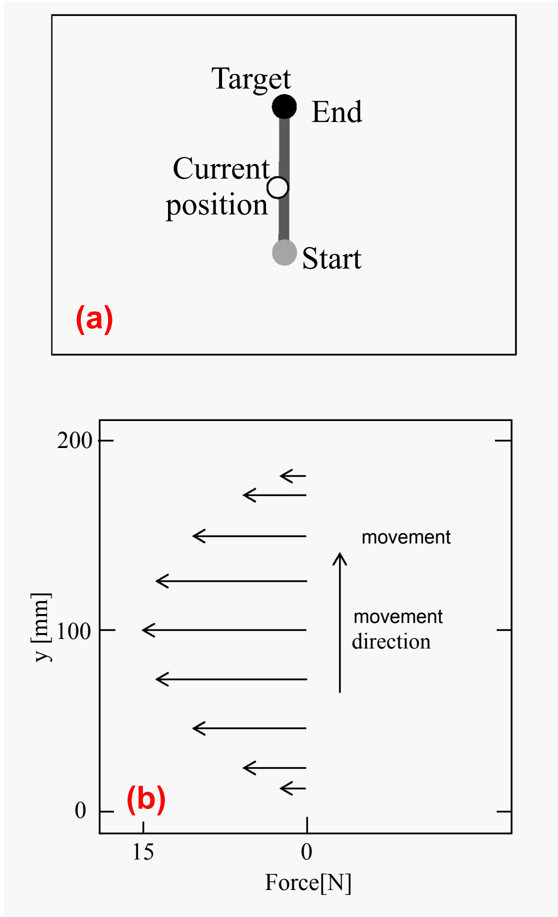

Figure 2: Example of experimental display (a) when the target point was located at the end point, and perpendicular forces with a bell-shaped velocity profile (b).

Reaching task

During all experimental sessions, the subjects were asked to make a reaching movement within two seconds from the start point to the end point displayed on a LCD monitor. Figure 2 shows an example of experimental display when the target point is located at the end point. A small white circle represents the current hand positions of the subject, and the start and end points were displayed as light gray circles as shown in the Figure 2. These start and end points were separated by a 20 cm distance on the horizontal plane of the robot workspace. The distance was selected by preliminary experiment to cover the primary range of hand activity, preventing extreme angles of shoulder and elbow joints. A black circle signifying the target point prompted the subject to make reaching movement in a predefined time sequence for target presentation at the start and the end point. Thus, the subject was asked to make a movement to reach toward the end point when the target point was moved from the start point to the end point. A straight dark gray line connecting the start point and target point is displayed to help guide the subjects in making a straight-line reaching motion. After each reaching movement, the subject was also asked to relax his/her arm while the robot manipulator moved the subject's hand slowly back to the start point. During the rest period, the subjects were asked to keep their posture and to simply relax.

Experimental conditions and procedures

The subject sat on a chair that was located midway between the two manipulators and was asked to hold onto the right knobs with their right hand during the force field adaptation phase. In the channel phases, depending on the experimental groups, the subjects were asked to grip the left knob with their left hand as well for bilateral movement. The Table 1 shows the experimental conditions which were performed by the subject of each group. In the passive condition, the robot guides the left hand of the subject to the end point based on a tracking control of the goal-directing trajectory; in the active non-loaded and loaded conditions, the subject moves his/her left hand to the target point based on visual information by himself/herself. Before starting the main experiment, the subjects had test trials for 5 minutes to get used to the experimental environment, matching their hand movements to movements of the controlled position in the monitor.

The experiments consisted of three phases: pre-channel phase, force field adaptation phase and post-channel phase. The pre- and post-channel phases consisted of 50 channel movements performed in the mechanical guide bounding the straight-line path from the start to end positions. The force field adaptation phase consisted of 150 movements in the perpendicular force field designed to perturb the subject from their un-adapted pattern of limb control during this simple reaching task. The conditions imposed to the left upper extremity were different for each group in the post-channel phase. The experimental procedure was carried out as follows:

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Group	Condition	Description
PG	Passive	robot guides the goal-directed movement
ANLG	Active	Non-loaded Voluntary movement with non-loaded
ALG	Active	Loaded Voluntary movement with the resistive force of 15[N]
CG	Control	unilateral movement

Table 1: Experimental conditions; PG, ANLG, ALG and CG mean the Passive Group, Active Non-Loaded Group, Active Loaded Group and Control group, respectively.

Step 1: The MVC of the subject is evaluated and subjects have test trials for 5 minutes.

Step 2: The subject is asked to perform 50 pre-channel movements with both of his/her hands for the three groups (PG, ANLG and ALG, hereafter, referred to as the bilateral group) while the left hand for the CG rests.

Step 3: After the pre-channel phase, the subject is asked to perform 150 movements in perpendicular field with his/her right hand while the left hand is kept on their lap.

Step 4: During the post-channel phase, the subject is asked to perform 50 movements in channel field with both his/her hands for bilateral group while the CG perform 50 channel field movements with just right hand. In the post-channel phase, the conditions imposed on the left hand for the PG and ALG are different; for the passive group, left hand was passively guided to the end point by the robot manipulator; and for active load group, the robot manipulator generate a resistive force of 15 N to impose on the opposite direction of reaching movement.

Measurement and analysis

To evaluate the subject performance we used measures of kinematic and dynamic behavior on simple goal-directed reaching tasks which is referred to in the research of Scheidt et al. [23]. The kinematic and dynamic performance was used to verify the adaptation and the disadaptation on the force field, respectively. Hand path error was defined as deviation of the hand from a straight-line trajectory passing between the start and end points. Dynamic performance was quantified by the peak hand force perpendicular to the direction of movement. This measure of dynamic performance was found to provide compelling evidence of motor adaptation without exposing subjects to periodic "catch trials." A catch is a null field trial in which the forces were unexpectedly removed; catch trials have been used to assess adaptation to the force field by characterizing its aftereffect. However, the recent evidence suggests that catch trials may themselves influence and degrade adaptation [31,32]. We refrained from applying the catch trials in order to prevent disturbing the adaptation process.

To verify the effect of conditions that were imposed on the left upper extremity, we used the property of persistence of motor adaptation which means the recovery time from adaptation to the force fields. The number of reaching movement trials required for the subject to recover from the adaptation (i.e., the disadaptation trial number) was measured as the persistence of motor adaptation in the post-channel phases. Therefore, the disadaptation trial number is given in the units [trials] since the sampling interval for measures of magnitude of the dynamic performance was 1 trial. The disadaptation trial number was determined when the magnitude of dynamic performance was smaller than 0.5N during the reaching movement in the post channel phase. For example, if the magnitude of dynamic performance of the subject is smaller than 0.5N in the fifteenth trial, the disadaptation trial number is 15. Based on the bilateral transfer aspect, the disadaptation trial number is varied by the conditions imposed on the left upper extremity.

The smaller disadaptation trial number can be induced by actively causing bilateral transfer. Thus, the result with smaller disadaptation trial number creates a condition for more effective bilateral movement training. By comparing the disadaptation trial number measured in each condition, we found the exact therapeutic condition necessary for planning of effective bilateral movement training.

Results

All subjects completed the Edinburgh handedness inventory, which is used to assess dominance of a person's right or left hand in daily activities. The range of their laterality quotients, obtained with a method reported by [29], ranged from 86. 8 to 100, where -100 means strongly left-handed and +100 means strongly right-handed on the

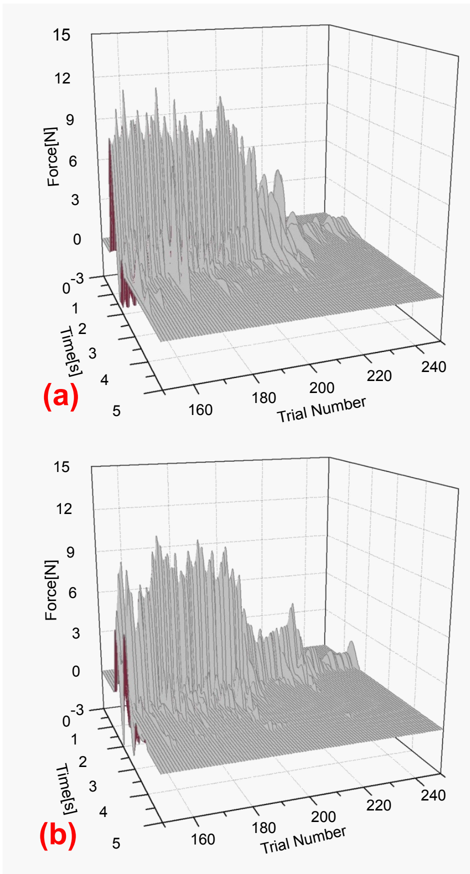

Figure 3: Hand force profiles perpendicular to the direction of movement on the trials immediately preceding and immediately following the transition from perpendicular field (trials 151-200) movements to channel field (201-250) movements. The hand profiles without kinematic errors (b) show that the recovery of motor adaptation was much slower than those with the kinematic errors (a).

Groups	Mean	SD
PG	20.80	4.38
ANLG	15.60	3.58
ALG	13	3.16
CG	38	6.71

Table 2: The disadaptation trial number; means (standard deviations) of the five subjects in the each group during post-channel phase. Since the sampling interval for measures of dynamic performance was 1 trial, the unit of evaluation variable is trials.

scale of -100 to 100. Therefore, all subjects had strongly right-handed laterality.

To verify the effect of conditions which were imposed on the left upper extremity, we evaluated the trial number of disadaptation in post-channel phase for four groups. Table 2 shows the means and the standard deviations of the evaluation variable for the five subjects in the each group during post-channel phase. Additionally, we applied the Mann-Whitney test which was a common nonparametric statistics to our results for the statistical verification. The results of Mann-Whitney test are discussed in the next sections.

Verification of persistence of motor adaptation

According to Scheidt et al. [23], when kinematic error were prevented by mechanical channel, recovery from motor adaptation was much slower compare with when subjects were allowed to make kinematic errors. In this study, we also verified the investigation result of Scheidt et al. [23] about persistence of motor adaptation. Figure 3a and 3b shows the hand force profiles perpendicular to the direction of movement which conducted by the two subjects when the kinematic errors were allowed to occur after removal perturbing forces (null field) or prevented by a mechanical channel with enforce a straight path on the movement, respectively. Figure 3 shows hand force profile, indicated that the recovery of motor adaptation was much slower when the kinematic errors were prevented to occur by mechanical channel. The disadaptation trial number was 3 [trials] when kinematic errors were allowed to occur. As shown in the Figure 3b, while the kinematic error was prevented to occur, the persistence of motor adaptation was retained much longer and disadaptation trial number was 48 [trials]. Based on this result, we applied the characteristic of the persistence of motor adaptation to our evaluation method.

Comparison between the active and passive conditions

Figure 4 shows the hand force profiles of one subject of four groups. Based on the results shown in Table 2, the comparison between active and passive conditions which were imposed on the left upper extremity indicates that, in the active conditions(both non-loaded and loaded), the trial number of disadaptation was smaller than the passive conditions. The hand force profiles of one subject of PG (a), ANLG (b) and ALG (c) also showed that the passive conditions retained the persistence of adaptation longer than two active groups. Figure 5 shows the results of Mann-Whitney test for the disadaptation trial number with respect to the four conditions group. Note that the p-values of the comparison between PG and ANLG are 0.07, thus there was marginally

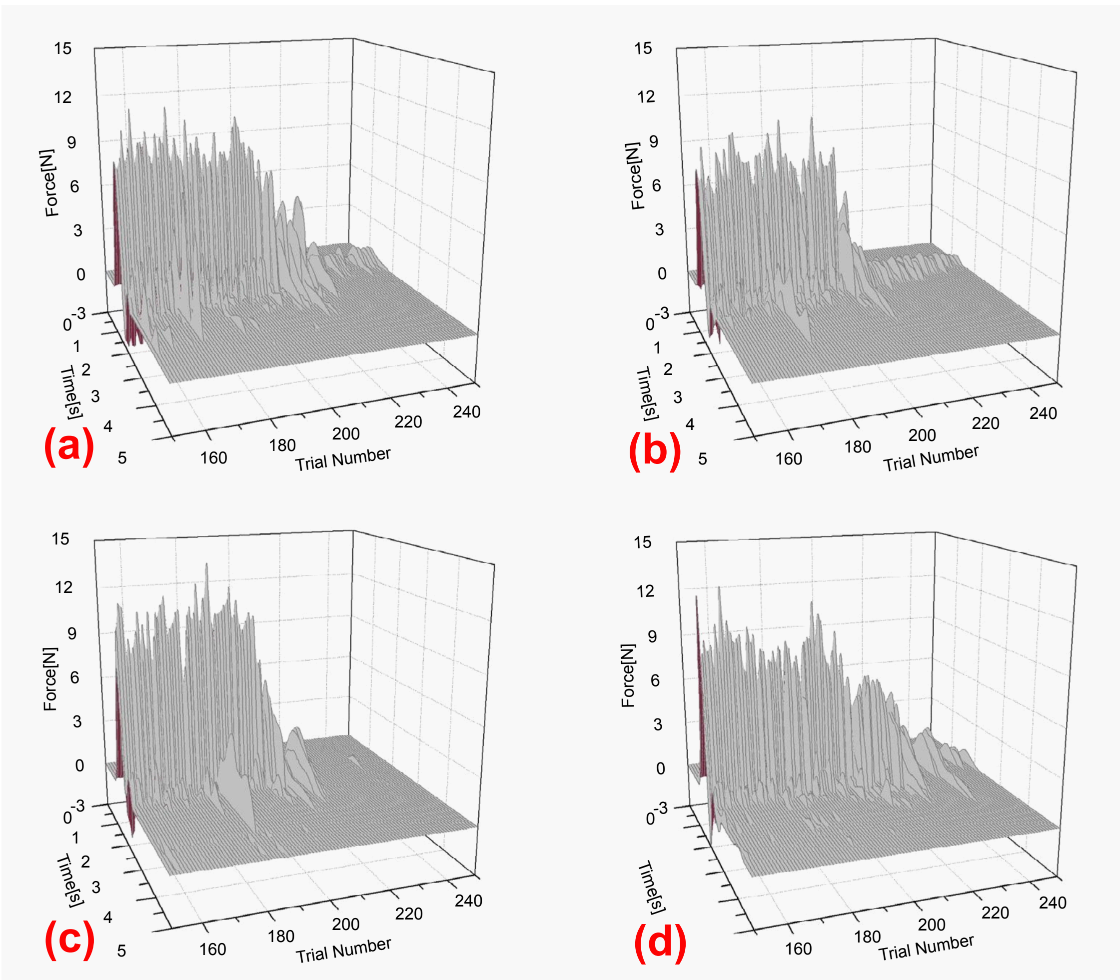

Figure 4: Hand force profiles perpendicular to the direction of movement on the trials immediately preceding and immediately following the transition from perpendicular field (trials 151-200) movements to channel field (201-250) movements in four conditions: PG (a), ANLG (b), ALG (c) and CG (d).

significant different while the comparison result between PG and LG showed the significant different (p<0.05). Even though the comparison result between PG and ANLG showed that there was marginally significant difference, the results showed that both active conditions (ANLG and ALG) promoted the dissipation of the motor adaptation than the passive condition.

Comparison between the bilateral and unimanual conditions

By the comparison between the bilateral group (PG, ANLG and ALG) and the CG, we verified the effectiveness of bilateral movement training. As shown in the Table 2, the trial number of disadaptation in the bilateral group smaller than the CG (unimanual group). And the hand force profiles of one subject of CG also showed that the motor adaptation retained the persistence of adaptation longer than the PG (a), ANLG (b) and ALG (c) as shown in the Figure 4. According to the Figure 5, the results of Mann-Whitney test showed that there are significant difference between unimanual and bimanual movement. Note that the p-values of the comparison between unimanual and bilateral is less than 0.01. These results reveal that the bilateral movement training is better than the unimanual one.

Comparison between the loaded and non-loaded conditions

To verify the effect of resistive load on the movement, we compared the result of the ANLG and ALG. As shown in the Figure 4b and 4c, the hand force profiles showed that the subject of active non-loaded group retained the persistence of motor adaptation longer than active loaded group and Table 2 also showed that the trial number of disadaptation for ANLG was larger than results of ALG. However, according to the Mann-Whitney test shown in the Figure 5, there was no significant different between active non-loaded and active loaded groups (p<0.29).

Discussion

Although robot-aided rehabilitation systems have benefit to freely create various bilateral movement training which induce much more interaction between left and right hemisphere for effective rehabilitation, most developed robot-aided rehabilitation systems provide bimanual symmetric motions through measuring the position of the normal upper limb and mirroring the motion to the impaired limb using robot manipulator or exoskeleton type robotic devices. Therefore, in this study, we investigate that the effect of conditions which are imposed on the one upper extremity to plan bilateral movement training causes the more interaction between upper extremities. We used four conditions: passive, active non loaded, active loaded, and control (don't move). Using the virtual impairment based on the human motor adaptation, healthy subjects were participated with one of four conditions. The trial number of disadaptation during bilateral movement task was measured as the evaluation variable. By comparing the trial number of disadaptation in each condition, we found the exact condition for planning of effective bilateral movement training. The comparison result of the evaluation variable in the active and the passive conditions, the trial number of disadaptation was much smaller in the active condition than in the passive. In other words, the bilateral transfer of sensory information in active condition causes the much more interaction between both upper extremities; this was consistent with the results discussed in the [19] which bilateral transfer of propriception was actively occurred with the voluntary movement. Therefore, active bilateral movement training would cause much more interactions between upper extremities is better for upper extremities rehabilitation.

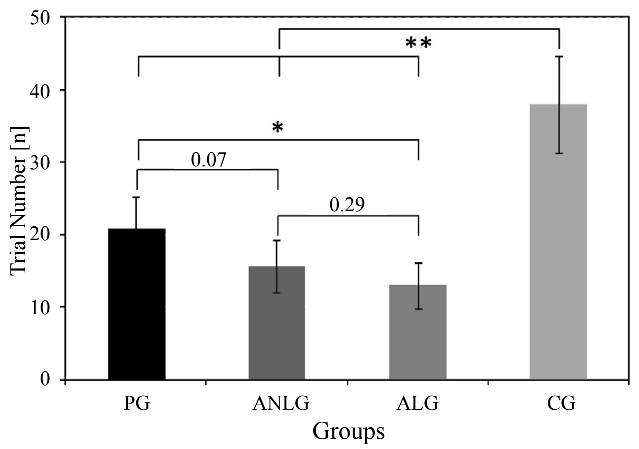

Figure 5: Mean of the five subjects' trial number for the each group. The values of the Mann-Whitney test are shown in the figures, where * means p<0. 05 and ** means p<0. 01 or the p-value is shown.

We also compared the active non-loaded and active loaded conditions. Even though, the comparison result showed that the trial number of disadaptation of the active non-loaded group was larger than active loaded group, there was no significant difference between two groups within statistical analysis. The magnitude of load for active loaded group set with the 15N for all subjects of active loaded group. According to the [20], the bilateral transfer of force perception is the function of the simultaneity and the magnitude of force. Thus, the setting force value for active non-loaded group should be considered to adaptive each subject's individual difference such as muscle strength. Additionally, by the comparison between the bilateral group and the unilateral group, we verified the effectiveness of bilateral movement training for upper extremity rehabilitation.

Conclusion

In this study, using the results of the our previous two research results [19,20], we focused on the finding the exact therapeutic condition which was imposed on the one upper extremity (left hand in this study) for planning of effective bilateral movement training which induce the much more interaction between upper extremities based on the bilateral transfer aspect. The bilateral transfer of sensory information is one kind of the interactions between upper extremities and the conditions actively causing the bilateral transfer will induce the neural plasticity for the rehabilitation. The experimental result indicated that active movements with resistive force condition induce much more interaction between upper extremities. Therefore, we found that, for more effective bilateral training, robot-aided system supports the bilateral movement should set the active movements with resistive force condition for unimpaired upper extremity.

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