

Bilateral Transfer in Active and Passive Guidance-Reproduction of Upper Limbs Motion: Effect of Proprioception and Handedness*

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Abstract

Recently, bilateral movement training based on robot-assisted rehabilitation systems has been attracting a lot of attention as a post-stroke motor rehabilitation protocol. Since humans generate coordinated motions based on their motor and sensory system, investigation of the innate properties of human motor and sensory systems may provide insight into planning of effective bilateral movement training in motion. In this study, therefore, we investigate the effects of proprioception and handedness on the movements of the contra-lateral upper limb, under both active and passive robot guidance conditions of the robot manipulators. Active and passive guidance-reproduction based bimanual tasks were used in this study; in these the subject is asked to hold both right and left knobs installed at the end-effectors of two robot manipulators. The results indicate that better reproducing performance was obtained when the proprioceptive input was acquired from the active guidance condition.

Key words: Proprioception, Bilateral Movement, Active/Passive, Reproduction, Handedness, Rehabilitation

1. Introduction

With the progress of the aging society, the number of stroke or spinal cord injury patients who need rehabilitation has been steadily increasing in the world. The number of physiotherapists is not sufficient, and one-on-one manual therapy has clear limitations because it is labor-intensive, time consuming, and lacks exact repeatability. Thus many rehabilitation systems have been developed based on the application of robot technology.⁽¹⁾ In robot-assisted rehabilitation therapy, the duration and the number of training sessions can be increased without increasing the burden on physiotherapists. Furthermore, robot-assisted rehabilitation systems provide quantitative measurement to support observation and evaluation of the rehabilitation protocol.⁽²⁾

Since most stroke or spinal cord injury patients suffer hemiplegia, many robot-assisted rehabilitation systems have been developed to support training that focuses on one side of the upper limbs with disabilities.⁽³⁾ However, many daily tasks such as driving a car, reaching for an object, and opening a container naturally require the coordinated participation of both hands.⁽⁴⁾ This provides a rationale for the incorporation of bilateral

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movements into upper limb rehabilitation protocols.⁽⁵⁾ Additionally, clinical evidence from fMRI and TMS based studies of neural plasticity⁽⁶⁾ and brain activation^{(7),(8)} support 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, the critical training parameters that underlie the efficiency of bilateral movement have not been clarified. For example, cortico-motor facilitation under synchronous conditions was reported to be similar to facilitation under asynchronous conditions in Stinear et al.⁽¹⁰⁾ For the asynchronous condition, a phase shift of 60 degrees was imposed upon the movements of the contra-lateral upper limb.

For planning appropriate rehabilitation therapy, the evaluation and measurement of motor systems or sensory systems is one of the most important processes. Although robot-assisted rehabilitation systems have clear benefits such as repeatability and availability, the efficacy of training highly depends on how accurately the patient's bodily condition is evaluated.⁽¹¹⁾ Therefore, more precise evaluation processes are needed to design robot-assisted rehabilitation systems for providing appropriate forces and training movements which are adaptive to each patient. In conventional physical therapy, the evaluation of proprioception while training is considered suitable for use in clinical method because it has several distinct benefits such as reliance on motor abilities and high resolution.⁽¹²⁾ For example, one evaluation method of proprioception consists of moving a subject's joint to a certain position and then asking the subject to reproduce the set joint position and movement.⁽¹³⁾ For application of this kind of method to a robot-assisted rehabilitation system with bilateral movement training, it is essential to investigate the relationship between proprioceptions of the left and right arms. Additionally, due to the handedness, the two upper limbs have an asymmetrical neural organization in the human motor system.⁽¹⁴⁾ Therefore, to investigate the relationship between upper limbs, the effect of handedness also should be considered.

One type of the sensory system, proprioception is generally believed to control the awareness of joint angle, motion and force and to play an important role in the control of goal-directed movements.⁽¹⁵⁾ Most of the researchers agree that muscle spindles are the primary source of proprioception, although signals arising from the joints, tendons and cutaneous receptors also contribute to awareness. Since the muscle spindles are subject to central fusimotor control,⁽¹⁶⁾ the sensitivity of muscle spindle is altered by muscle activity patterns and commands in passive and active movements.⁽¹⁷⁾ Therefore, many researchers apply this characteristic of muscle spindle to their experimental method when they investigate the characteristics or role of proprioception in motion.⁽¹⁶⁾

The objective of this study is the investigation of the relationship between left and right arm proprioceptions and the effect of handedness for planning more appropriate bilateral movement training. The effect of one upper limb's proprioception on the movement of the other upper limb was verified by the differences in reproducing performance during both active and passive guidance conditions. Active and passive guidance-reproduction in bimanual tasks were used in this study; in these the subject was asked to grip both right and left knobs installed at the end-effectors of two robot manipulators. In the passive guidance condition, the robot guides one hand of the subject to the target based on a tracking control of the goal-directing trajectory; in the active guidance condition, the subject moves his/her hand to the target point based on visual information by himself/herself. In order to evaluate the proprioceptive signal acquired from the guidance based reaching motion, the subjects are asked to reproduce the mirror-symmetrical motion with respect to the motion of the contra-lateral upper limb. By comparing the experimental results obtained in the left(arm)-guidance-right(arm)-reproduction task and the right-guidance-left-reproduction task in both active and passive guidance conditions, we have isolated the effects of the handedness.

2. Method

2.1 Subjects

Ten 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. In order to evaluate the handedness of each subject, we used the Edinburgh Handedness inventory, a measurement scale to assess the dominance of a person's right or left hand in everyday activities.⁽¹⁸⁾

2.2 Experimental apparatus

The experimental apparatus consists of two serial manipulators with 6 degrees of freedom (PA-10, Mitsubishi Heavy Industries, Ltd). At each manipulator, 6-axis force/torque sensor (NITTA corporation) is attached between the robot end-effector and the knob. The motions of manipulator are restricted on the horizontal plane (xy plane in Fig.1). The monitor is set 1.5 meters in front of the subjects who sit on the chair. During the experiments, the subject is asked to concentrate on the monitor.

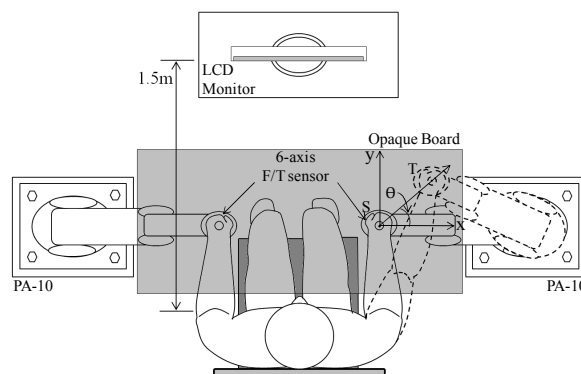


Fig.1. Top view of experimental setup

In the active guidance condition, the positions with respect to x and y of the end-effector 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.⁽¹⁹⁾

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

The inertia (M), viscosity (D) and stiffness (K) are set to 0.1[kg], 10[N/ms] and 0[N/m], respectively. We choose these values, based on the results of preliminary experiments, so that the subject may move the robot end-effector with sufficiently small muscle force. The variable z expresses the position x or y corresponding to the F_x or F_y , which is the forces of x or y direction measured from the force/torque sensor. F was measured with a sampling frequency of 100Hz. Therefore, the subject controls the position of the end-effector through his/her voluntary movement. In contrast, for the passive guidance condition, the robot guides one hand of the subject from the start point(S) to the target point(T), as shown in Fig. 1, based on a position control of the predefined goal-directing straight line trajectory in the isokinetic condition. The straight-line distance from the start point to the target point is 20cm, and the angle(θ) from the x -axis to the straight line trajectory is 45 degrees.

In order to ensure that the subject controls their hands based on proprioceptive feedback in response to the visual information of the monitor, an opaque board is placed above the knobs to prevent the subjects from viewing their hand positions. During the experiments, the positions of the end-effector which represented the actual positions of the subject's hand and the target point were recorded with a sampling frequency of 100Hz for evaluation of the

reproducing performance.

Since the sensitivity of muscle spindles can be affected by external forces, including those that restrain the posture of the arm with straps or an arm supporter, we did not restrain the arm posture. Although the human arm has 7-degrees of freedom and can produce the same hand trajectory with various arm configurations to reach a specific position, people typically generate a reaching motion based on minimizing the magnitude of total work done by joint torques and natural motion trajectory. Thus, the joint trajectories of typical unrestrained movements tend to be consistent both within and across subjects.⁽²⁰⁾ In the experiment, the arm configuration of the subjects did not vary to an extent which could affect the experimental results. Therefore, the subjects were asked to adopt a comfortable posture to perform the experiment and to lean back in the chair to maintain a trunk position similar to that shown in the Fig. 1.

2.3 Targets

Two knobs are 40cm apart from each other. Fig. 2 illustrates an example of the task execution, where the target, start and current position of the right arm are shown in the monitor. The location of the target was selected by preliminary experiment to cover the primary range of hand activity, preventing extreme angles at shoulder and elbow joints. To ensure reproduction of the positions of the target point based on the proprioceptive sensory feedback via the contra-lateral hand movement, the target points for both upper limbs were located symmetrically with respect to the sagittal plane of the subject. A small white circle is displayed for the hand position of the subject; and the target and start points are displayed as small black and light gray circles, respectively. In both guidance modes, when the black circle is near the target point, a straight dark gray line connecting the start point and target point is displayed to help guidance the subjects in making a straight-line reaching motion. We evaluate the tracking performances of both arms to the target points.

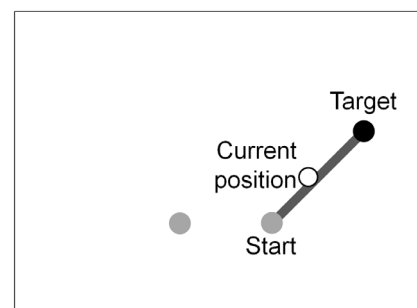


Fig.2. Example of experimental display

2.4 Preliminary experiments

To determine the appropriate location of the target, we evaluated the reproducing performance during the guidance and reproduction unimanual task by repeatedly extending the distance between the start and the target. The subjects were asked to reproduce the same location as the guided location from robot manipulator based on their proprioceptive sensory feedback, which was obtained by a guidance-based reaching motion. Two right-handed subjects performed the task with their dominant(right) hand. Based on this experiment, the appropriate location of the target was determined to be 20cm from the start location. This is not a full length stretch, because in the case of a full length stretch the shoulder and elbow joints extend to the extreme angles, the hand position can be perceived by the joint angle alone, without any other proprioceptive feedback. In cases when the distance is shorter than 10cm, the proprioceptive feedback for the perception of hand position relies more on the joint angle than on other receptors, such as muscle spindles and tendons. Since the height of all subjects ranged from 165cm to 185cm, statistically, the

length of upper limbs ranged from 72cm to 76cm.⁽²¹⁾ Additionally, Mark et al. reported that the torso started to move when subjects extended their upper limb further than 90% of their upper limb length.⁽²²⁾ Therefore, we confirmed 20 cm as the appropriate distance for the purpose of our experiments.

The gamma motor neurons are the efferent component of the central fusimotor system, by which the central nervous system controls and modifies the sensitivity of muscle spindles. The central fusimotor system refers to the combination of muscle spindles and gamma motor neurons. The sensitivity of muscle spindle can not be changed by the muscle force magnitude, but only by muscle activity patterns in active and passive movements. Therefore, the muscle spindle can provide proprioceptive feedback for the movement, position and extension of muscles with the same sensitivity across the entire range of motion.⁽²³⁾ However, according to Walsh et al.,⁽²⁴⁾ the sensitivity of muscle spindle is affected by muscle fatigue. To avoid this effect, we performed an experiment to find the coefficients M, D and K in Eq. (1) and used this to determine the magnitude of the impedance so that the subject could move the robot end-effector with sufficiently small muscle force.

2.5 Experimental procedure

The subject sat on a chair that was located in midway between the two manipulators and held onto the left and right knobs with their left and right hands, respectively. Before starting the main experiment, the subjects had test trials for 3 minutes to get used to the experimental environment, matching their hand movements to those of the controlled position in the monitor.

TABLE 1
EXPERIMENT CONDITIONS

Conditions (Abbreviation)	Guidance	Reproduction	Trial number
C1(PG-LR)	Passively right	Left	15
C2(AG-LR)	Actively right	Left	15
C3(PG-RR)	Passively left	Right	15
C4(AG-RR)	Actively left	Right	15

PG and AG imply the passive and active guidance modes, respectively. LR and RR imply the left hand and right hand reproduction modes, respectively.

To achieve the objective of this study, the 4 experimental conditions shown in Table.1 were used to compare the subject's reproducing performances. In all conditions, the subject was asked to move one of their hands to the target point in 2 seconds (guidance mode). After stopping around the target point for 3 seconds, the robot manipulator returned the subject's hand to the start point. Since the subjects could not see the real position of their hands directly, the subject recognized the target point by the proprioceptive signals of their arm. However, in conditions of C1 and C3 the robot guided one hand of the subject in trajectory control mode, while in the conditions of C2 and C4 the subject consciously moved his hand to the target point by means of the displayed visual information. After returning to the start point and having a 5 second delay, in order to allow the subject time to evaluate the proprioceptive signals acquired from the guidance based reaching movement, the subject was asked to reproduce the reaching motion with their contra-lateral hand to the symmetrically located target point (reproduction mode) in the same amount of time as the guidance mode. According to a predetermined command, the target point was shown on the monitor. Note that in the guidance mode, the subject can recognize the positions of both the target point and the current point of his/her hand in both active and passive conditions from the monitor. In the reproduction mode, however, the subject can recognize only the position

of the target point from the monitor. Therefore, to reproduce the symmetrical reaching motion, the subject has to refer to the proprioception bilaterally transferred from the reaching motion in the guidance mode.

2.5.1 Passive guidance condition

The experimental procedure for the passive guidance conditions, C1 and C3, can be carried out as follows. The Fig. 3 shows the current position and velocity of the end-effector as a time series. For this condition, the robot guides one hand of the subject based on a position control with an isokinetic condition, as shown in the Fig. 3.

- Step 1: One hand(right hand in C1 and left hand in C3) of the subject is passively guided to the target point by the robot manipulator. The robot manipulator takes a straight line trajectory as shown in Fig 2. It takes about 2 seconds to reach the target point from the start point as shown in the Fig. 3.
- Step 2: After reaching the target point, the robot manipulator stops at the target point for 3 seconds and then returns the knob that the subject holds to the start point.
- Step 3: After returning to the start point, the subjects wait for 5 seconds.
- Step 4: Based on the proprioceptive signals of the guided hand, the subject reproduces the mirror-symmetrical movement with their contra-lateral hand (left hand in C1 and right hand in C3) with respect to the initial guidance path. After reproducing the symmetrical movement and moving his hand to the symmetrically-located target points, the subject is asked to wait until the robot manipulator automatically returns to the start point. The time needed for Step 4 is approximately 5 seconds, the same as the time period of the guidance mode (the total time of Step 1 and Step 2).
- Step 5: The robot manipulator returns the knob to the start point. This takes about 2 seconds.
- Step 6: After the knob returns to the start point, the subject waits for 5 seconds.
- Step 7: If all of the predefined target points were presented, we terminate the process; otherwise, the next target point is set in the monitor and Step 1 follows.

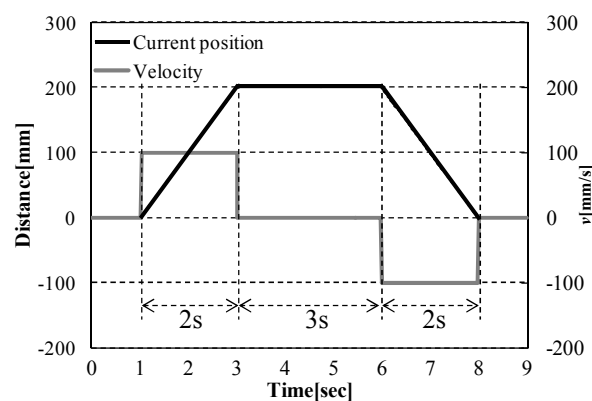


Fig.3. The current position and velocity of end-effector in passive guidance.

2.5.2 Active guidance condition

For the active guidance conditions, C2 and C4, the experimental procedure can be carried out in a similar way. The only difference between the active guidance condition and the passive guidance condition is in step 1, which follows. The Fig. 4 shows the mean values of current position and velocity of one subject for 15 trials as a time series. The subject reached the target point in almost the same time for all 15 trials.

- Step 1: The subject moves one of their hands (right hand in C2 and left hand in C4) to

the target point by using his/her motor system based on the current point of his/her hand shown in the monitor. After reaching to the target point, the subject is asked to keep hold of the knob until returning to the start point. For Step 1, time is set to 5 seconds, the same time period as the passive guidance mode (the total time of Step 1 and Step 2 in the passive guidance condition).

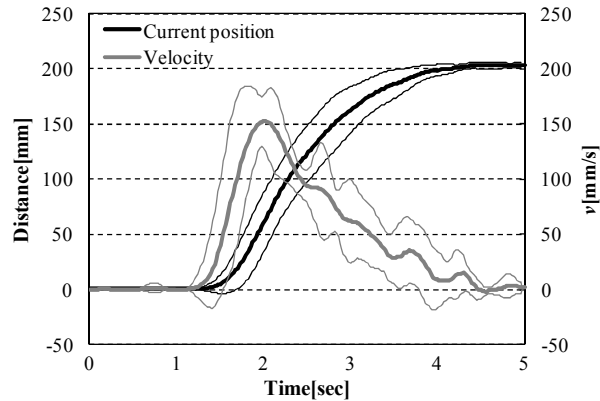


Fig.4. Mean values of current position and velocity of one subject for 15 trials. Thick lines show changes in the mean position and velocity, and thin lines indicate the standard deviation for these means.

15 trials were performed in each condition. Each condition of Table 1 was performed once by each subject. In theory, iterative tasks may be affected by learning and order effects. To avoid this effect, we randomly determined the order of the experimental conditions for each subject and had each subject take a 10 minute break between conditions in the experiment. Note that through comparison between C1 and C3 the passive guidance condition and between C2 and C4 the active guidance condition, the effect of handedness can be investigated.

2.6 Measurements and analysis

The task performance was measured by how well the subject reproduced the target point that was mirror-symmetrically positioned with respect to their contra-lateral hand in the guidance mode. Fig. 5 shows four variables used evaluate the reproduction performance: E, S and T are the positions of the end point controlled by the subject, the position of the start point, and the position of the target point, respectively; d_a is the absolute distance between E and T; and d_r measures the range which is the difference between the distance from the start point to the target point and the distance from start point to the position of the end point; and θ_d is the angular difference between E and T. We also calculate the error area (A_e) as shown in the Fig. 5 which approximates the error, which may be defined as the integral of the difference between the target and actual trajectories.

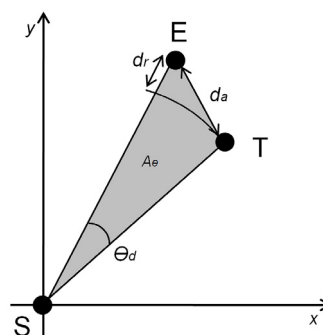


Fig.5. Illustration of dependent variables in the case of the right arm

In this study, we focus on spatial perception and do not take into consideration the temporal characteristics of the reproducing performance. A paired-sample t-test was applied to the four variables in order to detect the significant difference between active and passive guidance conditions and to investigate the effects of handedness. In order to apply the paired sample t-test to each evaluation variable, the data sets of each variable were tested for normality by use of SPSS version 16(SPSS Japan Inc.).

3. Experimental 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 in (Oldfield, 1971), ranged from 83.3 to 100, where -100 means strongly left-handed and +100 means strongly right-handed on the scale of -100 to 100. Therefore, all subjects had strongly right-handed laterality.

In order to verify how proprioception influences on the reproducing performance in the contralateral upper limb under active and passive guidance conditions, we measured the end-point of the upper limb performing the reproducing task and obtained the values of four evaluation variables. We applied a paired samples t-test to each evaluation variable. Table 2 shows the average values and the standard deviations of the evaluation variables for each condition of the ten subjects.

TABLE 2
EXPERIMENTAL RESULTS

Conditions	Absolute distance(mm)	Range (mm)	Angular deviation($^{\circ}$)	Error area (mm 2)
C1 (PG-LR)	71.96 (24.72)	55.58 (24.36)	-11.54 (4.57)	6183.25 (2466.15)
C2 (AG-LR)	60.55 (22.22)	46.27 (22.53)	-10.71 (4.11)	4079.51 (1639.16)
C3 (PG-RR)	34.01 (12.15)	29.48 (12.52)	-2.34 (5.43)	2111.33 (1328.40)
C4 (AG-RR)	28.41 (10.78)	23.87 (12.27)	-1.40 (3.38)	1026.87 (866.45)

Means (standard deviation) of absolute distance, range, angular deviation and error area in four conditions.

3.1 Comparison between the active and passive conditions

Fig. 6 shows the actual tracking trajectories of one subject in both passive(a) and active(b) guidance conditions in left-guidance-right-reproduction mode for 15 trials. In the case of the active guidance condition, the actual tracking trajectories were nearer to the ideal trajectory, and the positions of the end point controlled by the subject were closer to the target point than in the passive guidance condition. Based on the results shown in Table 2, the comparison between the active and passive guidance conditions (C1 and C2 for left hand reproduction mode and C3 and C4 for right hand reproduction mode) indicates that for both left and right hand reproduction modes, more accurate reproducing performance was obtained when the proprioceptive sensory feedback was acquired from the active guidance condition (C2 and C4). Fig. 8 shows the paired-samples t-test results for each variable; the upper two graphs of each variable indicate the significant difference between active and passive guidance conditions. Note that the p-values of range and angular deviation between C3 and C4 (the graphs in the upper left of b and c in Fig. 8) are 0.10 and 0.23, respectively. Except for these two cases, the results showed significant differences ($p < 0.05$) between the active and passive conditions in both left and right hand reproduction modes.

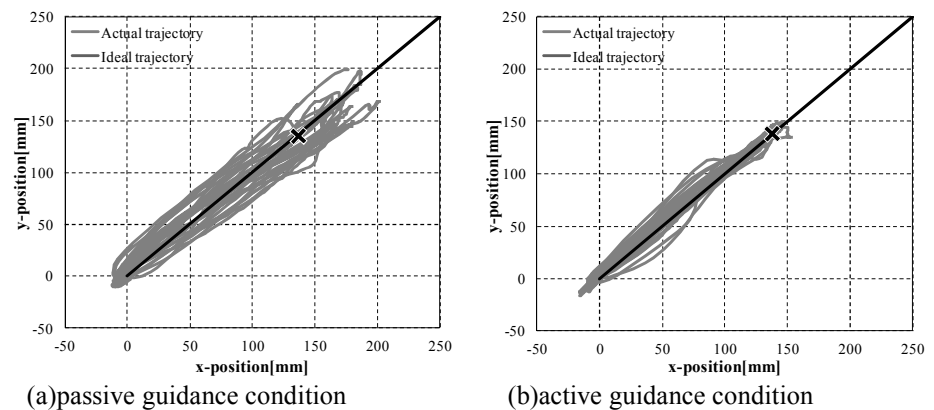


Fig.6. Tracking trajectories of one subject in active and passive conditions for left-guidance-right-reproduction mode(x is the target point).

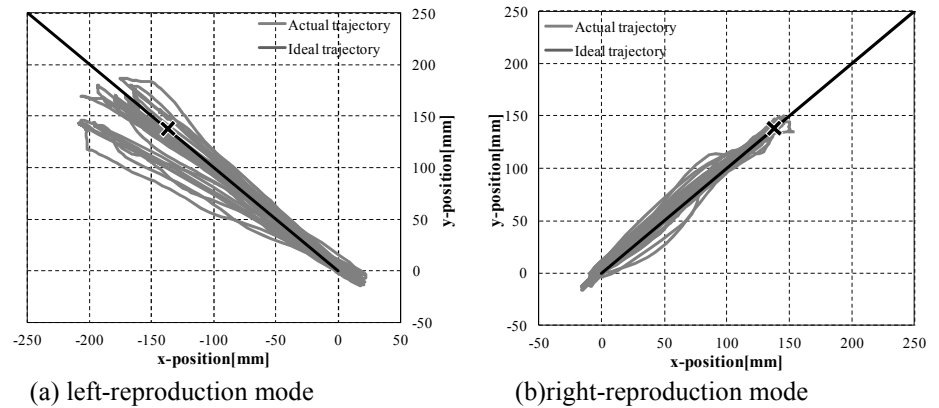
Although the subjects who participated in Laufer et al.⁽¹⁷⁾ and present study were different, since the evaluation of statistical result in both experiments can show the verification of the effectiveness of bilateral transfer based on the guidance and reproduction task, we evaluated the statistical results of unimanual tasks which were conducted in Laufer et al.⁽¹⁷⁾ and left-guidance-right-reproduction bimanual tasks (C3 and C4) in this study for both active and passive conditions. In the case of the active guidance condition, verification between unimanual and bimanual tasks which were performed with the dominant arm in the unimanual task and the bimanual C4 condition in this study was performed. The verification results of evaluation variables are as follows: the mean(standard deviation) of absolute distance was 24.5(14.2)mm and 28.41(10.78)mm in for the unimanual and bimanual tasks, respectively. The mean(standard deviation) of range were 3.7(19.1) mm in unimanual task and 23.87(12.27)mm in bimanual task. For angular deviation, means(standard deviations) were 0.2(9.4) degrees in the unimanual task and -1.40(3.38) degrees in the bimanual task. Thus, reproducing performance of unimanual task was more accurate than bimanual task, even though standard deviations of evaluation variables were bigger in unimanual task.

For the passive conditions, which were passive guidance and reproduction with dominant arm in the unimanual task and the C3 condition in this study, the verification results of evaluation variables are as follows: the means(standard deviations) of absolute distance were 29.7(20.2) mm and 34.01(12.15) mm in the unimanual task and bimanual task, respectively. The mean(standard deviation) of range were 9.9(23.7) mm in the unimanual task and 29.48(12.52)mm in the bimanual task. For angular deviation, results were 2.6(11.2) degrees in the unimanual task and -2.34(5.43) degrees in the bimanual task. Therefore, the verification results for each variable, except the angular deviation in passive condition, indicate that the reproducing performance of the unimanual task was more accurate than the reproducing performance of the bimanual task. Therefore, though the difference of reproducing performance between the unimanual and bimanual tasks was evaluated, the verification result indicated that the reproduction of mirror-symmetrical motion with respect to the motion of the contra-lateral upper limb can be occurred by the effectiveness of bilateral transfer.

3.2 Comparison between the left- and right-reproduction

To investigate the effect of handedness, we also compared the results of left- and right-reproduction modes. Fig. 7 shows the actual tracking trajectory of one subject for left- and right-reproduction modes in an active guidance condition. In the case of left-guidance-right-reproduction mode, the actual tracking trajectories were nearer the ideal trajectory and the positions of the end point which controlled by the subject were closer to the target point than in right-guidance-left-reproduction mode. Based on the results shown

in Table 2, the comparison between the left- and right-reproduction modes (C1 and C3 in the passive guidance condition and C2 and C4 in the active guidance condition) indicates that the reproducing performance of the dominant arm was more accurate in both active and passive guidance conditions. Therefore, the comparison results show that the direction of transfer of proprioceptive feedback is better from the left(nondominant) to the right(dominant) rather than the opposite, and this is true for both active and passive conditions.



(a) left-reproduction mode (b) right-reproduction mode
Fig.7. Tracking trajectories of one subject for left-reproduction and right-reproduction modes in active guidance condition(x is the target point).

The lower two graphs of each variable in Fig. 8 show the significant difference between left and right reproduction modes. In the case of the comparison between left- and right-reproduction modes, all four variables indicated a marginally significant difference ($p < 0.1$) between left- and right-reproduction modes.

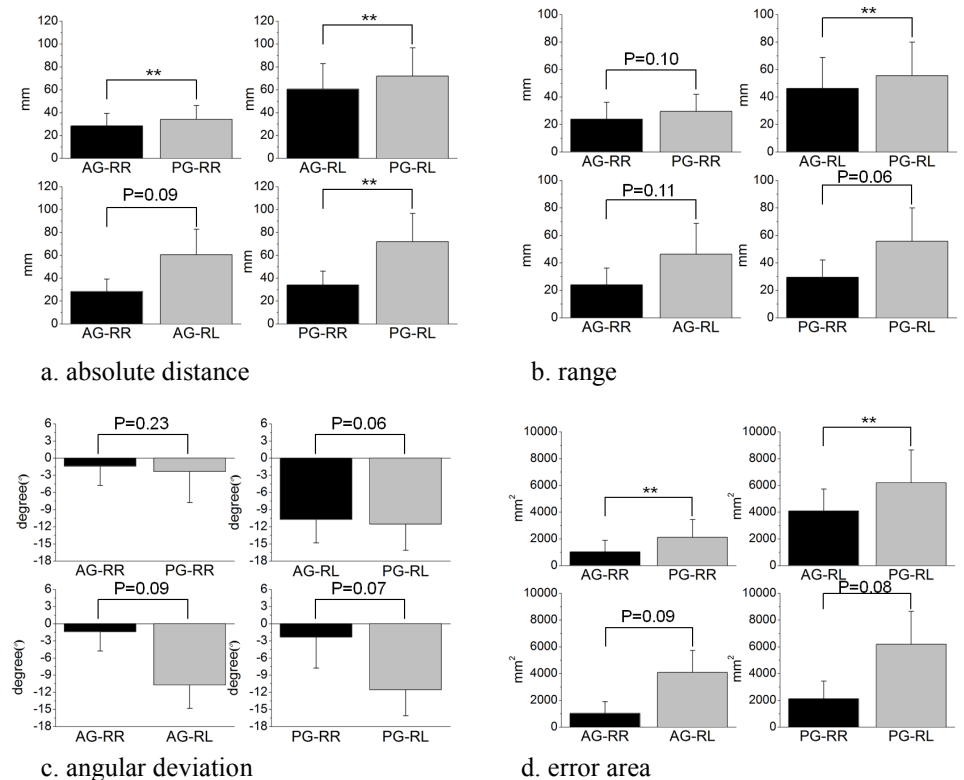


Fig.8. Mean of ten subjects for the four variables: absolute distance, range, angular difference and error area from a to d, respectively. The values of the paired-samples t-tests are shown in the figures, where ** means $p < 0.05$ or the p-value is shown.

4. Conclusion and Future work

Thanks to the development of robot technology, many robot-assisted rehabilitation systems for stroke or spinal cord injury patients have been developed. fMRI and TMS based studies and plenty of clinical evidence show that bilateral movement training has great promise in expediting progress toward stroke recovery in the upper limbs.⁽⁷⁾ Recently, therefore, bilateral movement training based on robot-assisted rehabilitation systems has been attracting a lot of attention as a post-stroke motor rehabilitation protocol. Since many daily tasks require coordinated participation of both hands, the understanding of bimanual coordination in healthy subjects may suggest neuronal specificity characteristics of patients who can benefit from bilateral movement training.⁽⁴⁾ In activities of daily living (ADL), humans generate coordinated motions based on their motor and sensory systems. Thus, the investigation of innate properties of the human motor or sensory systems can provide insight into planning more appropriate bilateral movement training; this has been the subject of intensive research.

To investigate the relationship between left and right arm proprioception and the effect of handedness, the active and passive guidance-reproduction based bimanual tasks were presented to the subjects. To verify the effect of one upper limb's proprioception on the movement of the other upper limb, we compared the reproducing performances between active and passive guidance conditions. The more accurate reproducing performance was obtained in the active guidance condition; this was consistent with the results obtained in the unimanual task.⁽¹⁷⁾ Additionally, according to the comparison results between unimanual tasks which were conducted in Laufer et al.⁽¹⁷⁾ and bimanual tasks in this study, reproducing performances of unimanual tasks were more accurate than in bimanual tasks for both active and passive conditions.

Since sensitivity of muscle spindle in the active guidance condition is more accurately tuned than in the passive guidance condition based on the characteristic of gamma motor neuron, it is clear that the proprioceptive sensory feedback should be better in the active guidance condition, and we suppose that this higher sensitivity of muscle spindle should cause a strong spatial working memory.⁽²⁵⁾ Consistent with this hypothesis, a more accurate reproducing performance was obtained when the proprioceptive sensory feedback was acquired from the active guidance condition in the bimanual tasks. The results of this study indicate that proprioceptive sensory feedback of one upper limb in both active and passive guidance conditions affected the reproducing performance of the other upper limb. Additionally, the results also showed that efferent central signals for motor command of one hand in active guidance condition contributed to the reproducing performance of the other hand in reproduction mode. In the passive condition, since the efferent central signals are likely to be absent, the subject is able to use only proprioceptive signals for the movement reproduction.

According to the research of Oliveira,⁽²⁶⁾ information about the movement that is acquired by the sensory system for one side of the limb is transferred to the other side, thus helping to effect its movement. A common assumption for this information exchange is that facilitation and interference effects are achieved because of the interhemispheric crosstalk through the corpus callosum in the brain. It is proposed that a hierarchy exists in the neural crosstalk of the central nervous system. High-level crosstalk is the transfer of abstract parameters of the movement such as slant, orientation, amplitude, and so on between the left and right cortical hemispheres via callosal connections. In contrast, low-level crosstalk occurs in the subcortical area while executing the movement specified by the abstract parameters.

In conventional physical therapy for upper limb rehabilitation, the stroke patient is passively guided in specific movements via physical or visual assistance by physiotherapists.

A robot-assisted rehabilitation system can perform these tasks and reduce the therapist's work load. Based on these investigations of proprioception, we suggest that evaluation of proprioception by the method described in this paper can be applied to plan the bimanual movement training for use in a robot-assisted rehabilitation system. Mirror-image training is one method of bimanual movement training based on a robot-assisted system; in this method, the unimpaired arm is passively or actively moved via specific movements, such as tracing trajectory or reaching motion, by the robot system to guide rehabilitation training for the impaired arm. Because mirror-image training depends on the characteristics of bilateral transfer and active guidance leads to better bilateral transfer of proprioception based on our investigation, active guidance mirror-image training will obtain better rehabilitation results than passive guidance. Additionally, when patients carry out rehabilitation trainings using intentional movement, it strengthens the motivation to participate in the rehabilitation training.

Motivation in rehabilitation therapy is one of the most important factors which should be considered and is frequently seen as a determinant of rehabilitation outcome. Thanks to the development of computer science and technology, in order to increase patient motivation, many robot-assisted rehabilitation systems consisting of interesting games, such as training tasks like putting pegs into a peg board and picking up coins and putting them into a bank, exist which practice activities of daily living.⁽²⁷⁾ Additionally, successful goal achievement can reinforce the importance of training in patients' minds and encourage them to continue. In other words, improved patient motivation is followed by better goal achievement. Based on the present study, we suggest ways to improve patient motivation by the training method for the upper limb rehabilitation with bimanual movement training. This training consists of active guidance in one upper limb and reproduction with the other upper limb, the same as the active guidance-reproduction condition used in this study. Since the proprioceptive sensory feedback and efferent central signals for motor command of one upper limb in the active guidance condition transfer to the other side and facilitate reproducing performance, the subject can get better goal achievement than in the unimanual movement task. Thus, the training increases the subject's motivation to exercise for longer periods of time and leads to better training efficacy.

We also investigated the effect of handedness in active and passive conditions. The experimental results showed that the reproducing performance of the dominant arm was better in both active and passive guidance conditions. Because the subjects were asked to reproduce the mirror-symmetrical motion with respect to the motion of their contra-lateral limb, handedness in sensory and motor systems between dominant and nondominant arms may result in difference of reproducing performances.

In this study, we investigated the effects of proprioception and handedness based on spatial bimanual coupling. We did not take into consideration the temporal characteristics of the reproducing performance. Since human sensory-motor system includes both spatial and temporal characteristics, the investigation of temporal characteristics can provide insights to the planning of effective bilateral movement training. Additional studies are necessary to investigate the role of the temporal coupling characteristics in bimanual coordination and planning of the effective bilateral movement training with the robot-assisted rehabilitation system in practice. Also, simultaneity in bilateral movement training is an important factor which affects bilateral transfer of proprioception. We plan to investigate the effect of simultaneity via simultaneous bimanual guidance-reproduction task, in which guidance and reproduction are performed at the same time.

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Appendix

Edinburgh Handedness Inventory

Your Initials: _____

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓ | ✓).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)		

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