NAGOYA UNIVERSITY

Study on Bilateral Transfer

for Planning Robot-Aided Bimanual Movement

Training

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Mechanical Science and Engineering

by

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2011

The dissertation of PARK Keunyoung
is approved and is acceptable in quality and form for
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Committee Chair

Nagoya University
2011

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Abstract of the Dissertation

Study on Bilateral Transfer

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The goal of this dissertation is to investigate the relationship between left and right side of human sensory system for planning more appropriate bilateral movement training for robot-aided rehabilitation systems. The main idea is to find the exact conditions that would cause much more interactions between upper extremities in order to plan effective bilateral movement training. To achieve this goal, we are focusing on the sensory system, especially, proprioception and force perception. The proprioception plays a functional important role in the control of goal-directed movements which are the most common physical therapy. And also, in robot-aided rehabilitation systems, according to the rehabilitation processes, robots commonly resist the movements of upper extremity or compensate the gravitational force of the upper extremity itself. Therefore, force perception is also important elements which should be considered.

The bilateral transfer of sensory information is one kind of the interactions between upper extremities. Thus, through the evaluation of the bilateral transfer of

the proprioception and force perception, the conditions which cause much more interactions between upper extremities can be defined. We hypothesize that the conditions which actively occur the bilateral transfer will induce the neural plasticity for the recovery and reorganization of lost motor function.

The primary novel contributions of this dissertation are:

 1. Investigation of bilateral transfer of proprioception

In chapter 2, the bilateral transfer of the proprioception which is important to perceive a movement such as predefined trajectory for rehabilitation is discussed. The effect of one upper limb's proprioception on the movement of the other upper limb is verified by the differences in reproducing performance during both active and passive guidance conditions of the robot manipulators.

2. Investigation of bilateral transfer of force perception

The objective of chapter 3 is to investigate the bilateral transfer of force perception. Through force perception-regeneration bimanual task in isometric condition, the results indicated that the bilateral transfer of force perception is functions of the simultaneity and the magnitude of forces and the bilateral transfer of force perception actively occurs regardless of the direction of force.

3. Planning of bilateral movement training

Chapter 4, using the results of the previous two chapter's studies, focuses on the planning of bilateral movement training which can induce the more interaction between upper extremities by the bilateral transfer of sensory information.

Chapter 1

Introduction

1.1 Robot-aided rehabilitation system

1.1.1 Motivation of robot-aided rehabilitation

Thanks to the development of medical science and technology, the life span of humans is extended continuously turning the world into aging societies; in the case of the Japan, the government reported the percentage of older people who exceed 65 years old is 20%(1 out of 5 people is older people) and predicted that it will be 30% and 40% in 2025 and 2050, respectively (report of Cabinet Office, Japan, 2010). According to the report of U.S. Census Bureau, An Aging World

2008 (World Health Organization, 2009), they reported that the world's older population increasing by an average of 870,000 people each month during the year and they also anticipated older people to outnumber young children. As shown in Figure 1.1, estimates of the world's population age structure at various points in the past indicated that children under age 5 have outnumbered older people. About 10 years after from now this will change. For the first time, people aged 65 and over are expected to outnumber children under age 5. The global population aged 65 and over was estimated to be 506 million as of midyear 2008, about 7 percent of the world's population. By 2040, the world is projected to have 1.3 billion older people which accounting for 14 percent of the total.

Figure 1.2 shows the summary mortality indexes and indicates the major cause of death changes in mortality by age group. The percentages of the disease of
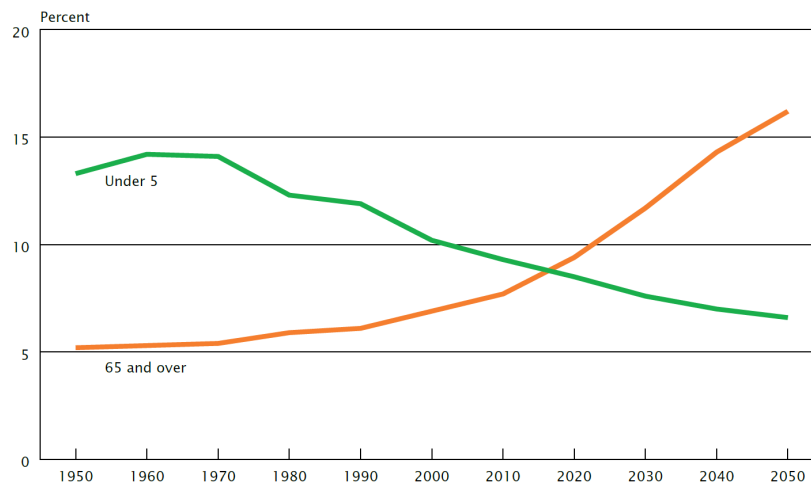
Figure 1.1 Young Children and Older People as a Percentage of Global Population: 1950 to 2050.
Source : United Nations Department of Economic and Social Affairs, 2007b.
(WorldHealth Organization, 2009)
From:www.census.gov/prod/2009pubs/p95-09-1.pdf

circulatory system such as cerebrovascular (stroke) increase significantly with advancing age. Thus, as the world became the aging societies, the stroke or spinal cord injured patients who need the rehabilitation are increasing in the world (World Health Organization, 2009). According to the World Health Organization, 15 million people suffer stroke worldwide each year, since 5 million die and another 5 million are permanently disabled. Stroke-induced motor impairments are amenable to rehabilitative treatment.

A recent evidence suggests that intensive therapy, longer training sessions per week and longer total training periods, improves movement recovery (Aisen et al. 1997). In studies of the upper extremity, repetitive movement practice improved movement ability of the hand and arm after stroke (Taub et al., 1999). This improved movement ability arose at least in part from cortical reorganization. It has been hypothesized that intensive therapy facilitates rewiring of the nerve or
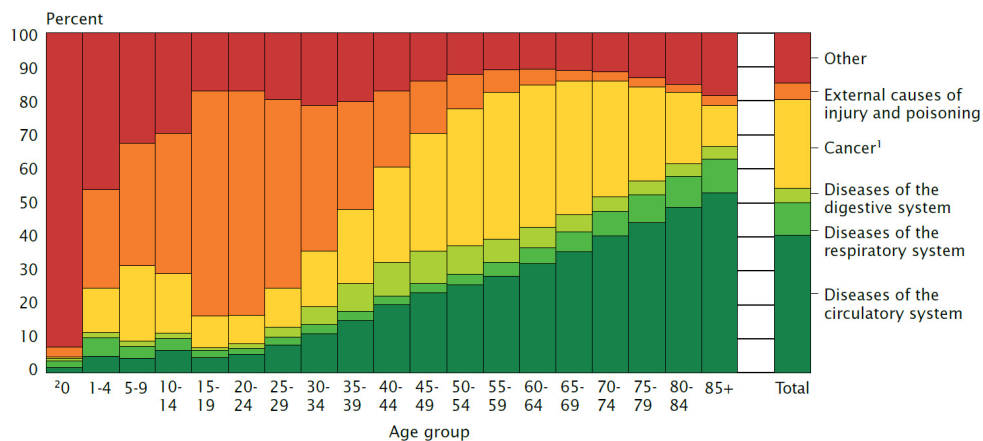
Figure 1.2 Major causes of death in the European Union by Age: 2001.
Source: Adapted from European Commission based on Eurostat mortality statistics. (World Health Organization, 2009)
From:www.census.gov/prod/2009pubs/p95-09-1.pdf

its pathway by the neural plasticity, with undamaged cortical areas assuming control functions previously allocated to damaged one (Liepert et al., 2000). However, such intensive therapy relies on the physiotherapist, where it is labor-intensive, time consuming and, therefore, expensive and lack of repeatability.

To address these problems, many researchers have been focusing on the development of the rehabilitation robot based on uses of robots and mechatronic devices to automate movement therapy after neurologic injury and disease (Reinkensmeyer, 2003). Rehabilitation robotics is a special branch of robotics which focuses on devices that can be used to help people recover from stroke-induced motor impairment. In robot-assisted 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 (Pange et al., 2006).

1.1.2 Main requirement for robot-aided rehabilitation systems

When researchers design and apply the rehabilitation robot, there are four main requirements for robot-aided rehabilitation system; psychological, medical, ergonomic, and suitability aspects (Riener et al., 2005). Psychological aspects should be considered so that the patients are motivated to participate rehabilitation training. Even though the robot-aided rehabilitation systems can support the

labor-intensive training, the physiotherapist still remains as the human controller in whom the patient has confidence. He or she plans the rehabilitation training, explains the robotic rehabilitation, adjusts the robot to the patient and executes the training by the robot system. The physiotherapist plays an important role for a successful rehabilitation process, whereas the robot just supports the therapy defined by the physiotherapist. Thus, the robot-aided rehabilitation system should remain rather 'invisible' and do not disturb the interaction between physiotherapist and patient. Furthermore, the robot-aided rehabilitation system should look 'human friendly' and behave accordingly, i.e. it should be safe, quiet and compliant, just as the physiotherapist's hand which is during one-on-one manual therapy.

Additionally, in the design and application of robot-aided rehabilitation system, medical aspects must also be considered to ensure a successful training. It is critical that the robot-aided rehabilitation system is adapted or adaptable to the human limb in terms of segment lengths, range of movement and the number of degrees-of-freedom. Although robot-aided rehabilitation system with a large number of freedom provides a various movement, with many anatomical joint axes involved. This makes the complex system and expensive. It still remains the question whether the therapeutic outcome can be maximized, if the robot-aided rehabilitation acts on the entire joints than on single joint. However, according to the Langhammer and Stanghelle (2000), the therapy focuses on activities of daily living which can be realized by the entire joint movement not only increases patient motivation but also yields the better therapeutic outcome.

As mentioned above, although the robot-aided rehabilitation systems can provide the therapy, the physiotherapist should stay from the beginning of the robotic therapy to the end of it. Therefore, when researchers are designing new robot-aided rehabilitation system, they must consider clinical standards to retain the compatibility with the conventional therapies. Therefore, based on the well-known scores such as Asworth scale and Fugl-Meyer Assessment, the robot-aided rehabilitation systems should provide the therapist with evaluation results which means the patient status and rehabilitation progress. As the robot-aided rehabilitation system replaces the physiotherapist's hand, well-defined sensor systems should be integrated to measure and evaluate the patient's effort and voluntary movement. These measured data also should be processed and presented to the physiotherapist, to assess the rehabilitation process.

Finally, even though robot-aided rehabilitation systems have clear benefits to support much longer duration and increased number of training sessions with repetitive movements for the intensive training, appropriate rehabilitation trainings should be considered to produce positive results. Many literatures reported the effects of robot-aided rehabilitation trainings as good as the conventional physical therapies. However, some researchers indicated that therapies with robot-aided rehabilitation systems caused no or less positive effects with respect to the conventional physical therapies. The patients have different lesion size and body location, severity of motor loss and the state such as acute or chronic after stroke. Therefore, in order to cause positive effects with robot-aided rehabilitation systems, the robot should provide more appropriate rehabilitation

trainings, based on the bodily conditions of each patient and planning the rehabilitation training based on the understanding of innate properties of human body systems.

According to the review of the requirements for the robot-aided rehabilitation system, there are four main requirements which should be considered to design and apply the rehabilitation robot. Among the four requirements, the suitability aspect for providing more appropriate rehabilitation training to cause the effective rehabilitation results using the robot-aided rehabilitation systems is dealt in this dissertation.

1.1.3 Review of robot-aided rehabilitation system for upper extremity

The goal of arm therapy is to recover motor function, improve movement coordination, learn new motion strategies and prevent secondary complications such as muscle atrophy and spasticity. The intensive movement practice facilitates positive effect on the motor function. Especially, task-oriented repetitive movements can improve muscle strength and reorganization of movement coordination in patients after stroke. Robot-aided rehabilitation system can support the movement therapy which is labor-intensive training, and they can be categorized into passive, active, interactive systems (Riener et al., 2005). In passive systems, extremities are passively stabilized, fixed or limited in the range of movement by the stiff frames, bearings and pulleys and ropes with

counter-weights. The Swedish Helparm is an example of passive system based on counter balances which are connected to the patient's upper extremity by ropes and pulleys to support the weight of the upper extremity during reaching movements. Active systems consist of electromechanical, pneumatic, hydraulic and other actuators to move extremities actively. Therefore, the active systems are open-loop controlled, or simple position control strategies are implemented. Interactive systems are characterized by sophisticated control strategies which allow reaction to the patient's effort. Wolbrecht et al. developed a robotic rehabilitation systems called by Pneu-WREX. Their system is equipped with pneumatic actuators to support the "assistance-as-needed" by providing assistance only when the subject is unable to complete the movement (Wolbrecht et al., 2008). Another one example of interactive system is mirror image movement enhancer(MIME) (Lum et al., 2006) which support the bilateral movement training provide the bimanual symmetric motions through measuring the position of the unimpaired upper limb and mirroring the motion to the impaired limb using robot manipulator. Recently, among the three types of systems, interactive systems have been attracting a stronger attention, because of development of robotics and computer science such as virtual reality systems. Since most stroke or spinal cord injury patients suffer hemiplegia, weakness of one side of the body and most common conditions, many robot-aided rehabilitation systems have been developed to support training that focuses on one side of the upper extremities with disabilities (Nef et al., 2007; Krebs et al., 2007; Hesse et al., 2003; Harwin et al., 2001; Mihelj et al., 2008)

Although most stroke patients regain and recover the gait ability, 30%~66% of stroke survivors fail to regain functional recovery of the impaired upper extremity (Kwakkel et al., 1999). Therefore, stroke researchers and physiotherapists are trying to search for more effective upper extremity rehabilitation protocol for regaining voluntary upper extremity movement. A current prominent rehabilitation protocol for upper extremities is bilateral movement training. Many activities of daily living such as driving a car, reaching for an object, 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 (Swinnen et al., 2002). This provides a rationale for the incorporation of bilateral movement training into upper extremities rehabilitation protocols (Srewart et al., 2006).

1.2 Bilateral movement training for upper extremity rehabilitation

Based on the functional Magnetic Resonance Imaging (fMRI) and Transcranial Magnetic Stimulation (TMS) studies which analyze the brain activation and neural plasticity, many literatures support the efficacy of bilateral movement training as a potential rehabilitation protocol. The investigation of innate property of human such as interlimb coordination and bilateral transfer can provide insight into planning appropriate bilateral movement training; this has been the subject of intensive research.

1.2.1 Neural plasticity and bilateral movement training

Many literatures which speculated on the neural mechanisms underlying bilateral training informed stroke researcher or therapists about the brain's activation to training based on the non-invasive brain mapping techniques including fMRI and TMS (Summers et al., 2006; Staines et al., 2001). According to the current research, possible mechanism underlying the efficacy of bilateral movement training includes recruitment of the ipsilateral corticospinal pathways, increased control from the contralesional hemisphere and a normalization of inhibitory mechanisms. In a review of neural plasticity and rehabilitation, Cohen and Hallett (2003) reported that the discovery of nerve

growth factor lead to experiments on trophic effects later in life. In addition, motor cortex functions can be altered by individual motor experiences. Currently, neuroscientists accept this neural plasticity that the tendency of activity affects the mature brain (Cramer et al., 2000; Nudo et al., 2003). This neural plasticity has major implications for the types of rehabilitation training administered post-stroke. Based on behavioral and neurophysiological mechanisms, bilateral movement training has shown great promise in expending progress toward chronic stroke recovery in upper extremities (Cauraugh et al., 2005; Stoykov et al., 2009).

1.2.2 The investigation of innate properties of human for bilateral movement training

Most common assumption of the use of bilateral movement training is that symmetrical bilateral movements activate similar neural networks in both hemispheres when homologous muscle groups are simultaneously activated (Wenderoth et al., 2004). With stroke, neural networks are depleted because of damaged neurons. Symmetrical bilateral movements, therefore, may allow the activation of the undamaged hemisphere to increase activation of the damaged hemisphere and facilitate movement control of the impaired limb promoting neural plasticity. However, the results from studies of bimanual coordination in stroke patients have been mixed. For example, Cunningham et al. (2002) reported improvements in the smoothness and velocity profiles of the involved limb during bilateral training with an increased inertial load for simple elbow movements.

Other studies, on the contrary, have observed that the impaired side exerting a negative influence on the unimpaired side degrades movement performances of unimpaired side to match that of the impaired limb. Thus, the symmetry constraint exerts a powerful influence even when one of the limbs is severely impaired (Rice et al., 2001, Lewis et al., 2004). Factors such as differences in task complexity and level of impairment of participants across the studies may account for the lack of consistency in results. Even though the many research results support the effectiveness of bilateral movement training, the critical therapeutic parameters underlying bilateral effect have not been identified.

The investigation of innate properties of the human (or healthy subject) such as interlimb coordination and bilateral transfer, transfer of a skill learned on one side of the body to the other side, can provide insight into planning more appropriate bilateral movement training; this has been the subject of intensive research (Swinnen et al., 2002a). Human can naturally generate the coordination motion between two upper extremities in daily living. Therefore, recent research on interlimb coordination, how the two upper extremities interact, coupling and decoupling, has been the new approaches to rehabilitation. The analysis of relative phase angle and movement frequency between limbs is used to evaluate the characteristic of interlimb coordination (Swinnen et al., 2002b). For example, Malabet et al. (2010) investigated the bimanual symmetric motions based on a physical path tracking task with omni force feedback devices in multiple reference frames; joint space symmetry (JSS) where the motions are mirrored and the joints on each limb follow the same angles, visual symmetry (VS) where the hands

move in the same Cartesian directions, and point mirror symmetry (PMS) where the hands rotate around an arbitrary point in space. The results indicated that the tracking performance of visual symmetry (VS) reference frames was better than another one.

The majority of investigations of bilateral transfer is mainly conducted for the transfer direction, the effect of handedness and element of bilateral transfer: from right to left side of the body or vice versa, laterality and sensory or motor information (Sainburg et al., 2002). Criscimagna-Hemminger et al. (2003) 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. Based on the investigation of interlimb coordination and bilateral transfer, this can support the answer to the primary question how the upper extremities interact with each other when function in one of the limbs is less than normal one.

Robot-aided rehabilitation systems have clear benefit to freely construct various bilateral movement trainings which induce much more interactions between unimpaired and impaired upper extremities for effective rehabilitation therapy. Robot-aided rehabilitation systems provide the mechanical assistance to patient's impaired upper extremity to help complete a desired movement by supporting the desired movement trajectory or the desired force. For the assistance,

patient and robot-aided rehabilitation systems interact with each other by physical contact. Therefore, in the case of the robot-aided rehabilitation systems, sensory or motor systems to perceive a movement and resistive or assistive forces should be much more considered. Although the study of the interlimb coordination and bilateral transfer has undergone a tremendous evolution in the past decades, to plan appropriate bilateral movement trainings inducing much more interactions based on the robot-aided rehabilitation system, we need to understand the relationship between left and right side of sensory or motor system.

1.3 Background of bilateral movement training: effectiveness, and implementation

In this section, we review physiological studies of neuronal processes underlying effectiveness of bilateral movement training: three proposed neural mechanisms of bilateral movement training, typical bilateral movement training implemented by the researchers, and explains two background knowledge: neural cross talk and bilateral transfer.

1.3.1 Proposed neural mechanisms of bilateral movement training

Non-invasive brain mapping techniques, including fMRI and TMS, stroke researchers can investigate the brain's response and activation following the rehabilitation training. According to the current research, there are three possible neural mechanisms to support the effectiveness of bilateral movement training for upper extremities rehabilitation; recruitment of the ipsilateral corticospinal pathways, increased control from the contralesional hemisphere and a normalization of inhibitory mechanisms. These neural mechanisms are described as follows.

Ipsilateral corticospinal pathway

According to the physiological studies of the neuronal processes, there are

corticospinal pathways which do not cross at the pyramidal decussation in the brain-stem. It is known that the estimated percentage of uncrossed pathways is approximately 10~20%. Mudie and Matyas (2000) suggested that bilateral movement training could facilitate these uncrossed, ipsilateral pathways. In symmetrical movements, since there is a propensity for spatial and temporal parameters such as moving distance increases, coupled symmetrical movement of both upper extremities are more spatially and temporally stable than asymmetrical movement. Kelso et al. (2005) called this phenomenon as the symmetry constraint. Based on the symmetry constraint phenomenon, Cauraugh and Summers (2005) suggested that bilateral symmetrical movement training may induce the symmetry constraint by greater use of the ipsilateral pathways. Even though, at present, the role of ipsilateral pathways has not been clarified for upper extremity rehabilitation, recruitment of the ipsilateral pathways after stroke is considered as a possible neural mechanisms underlying effective rehabilitation by bilateral movement training (Netz et al., 1997).

Activation of healthy (contralesional) hemisphere

A variety of manifestations of neural reorganization occurs after stroke; the most well-known symptom is increases of the neuronal activity in the contralesional cortex. Although the activation of both hemispheres is common for healthy people during complex tasks, in some stroke patients, contralesional activation increases after injury and then declines as ipsilesional recovery progresses (Cramer, 2008). Thus, the function of increased contralesional

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activation is the subject of much debate for improving post-stroke motor functions (Debaere et al., 2004). Spraker et al. (2007), based on the fMRI study examining the effect of grip force amplitude, found that both contralateral and ipsilateral sensorimotor cortices in normal subjects revealed positive increases as a function of increasing force amplitude in percent signal change and activation level. As expected, the contralateral hemisphere had much more percent signal change and activation volume compared to the ipsilateral hemisphere. An fMRI study comparing stroke and normal subjects indicated that stroke subjects showed increased activation in the contralesional cortex as compared to the healthy subjects. According to Schaechter and Perdue (2008), the magnitude of activation in the contralesional cortex was even greater in the stroke subjects during a more complex task. Thus, a reasonable explanation for the increased activation in bilateral cortical recruitment is that the contralesional hemisphere becomes more involved in the control of movements after an injury, and this involvement is greatest during complex tasks. Although it is not clear whether these cortical manifestations are facilitory or inhibitory for improving post-stroke motor function, following bilateral movement training, the contralesional hemisphere has been implicated in stroke rehabilitation (Luft et al., 2004). However, the degree of contralesional activation which is related to resumption of post-stroke motor performance remains unclear.

Cortical inhibition and disinhibition

For the orchestrated and coordinated actions of both hands such as catching a

ball and tying shoelaces, our brain well establishes the balance of inhibition and disinhibition between the cortices. After a stroke, however, the balance of inhibition and disinhibition between the cortices is disrupted. Usually, the affected hemisphere has reduced the excitability, while the non-affected hemisphere has increased the excitability. According to Stinear et al. (2008), transcallosal inhibition from the ipsilesional hemisphere to the contralesional one is greatly decreased. Murase et al. (2004) indicated that there are abnormally high levels of inhibition transferred from the contralesional to the lesioned hemisphere. Although, inhibitory mechanisms return to more normal levels in the case of well-recovered stroke survivors, by persistence of disturbed inhibitory, upper extremity recovery may be negatively impacted. Stinear et al. (2008) asserted that the normalization of inhibition and disinhibition between the cortices is a possible neural mechanism to support the effectiveness of bilateral movement training for upper extremities rehabilitation.

1.3.2 Review of bilateral movement training

Constraint-induced movement therapy (CIMT), one kind of the unimanual movement training, is considered as the most well-established therapeutic method for upper extremities rehabilitation in the many literature (Taub et al., 1993; Wolf et al., 2006, 2008). The focus of CIMT is to combine restraint of the unimpaired upper extremity and intensive use of the impaired upper extremity. Constraint typically consists of placing a mitt on the unimpaired hand or a sling or splint on

the unimpaired arm, motivating the use of the impaired upper extremity when performing rehabilitation training tasks. However, this CIMT method has strict inclusion criteria which are only adaptive to more mildly impaired stroke survivors or more recovered patients. Nevertheless, positive results have been achieved through CIMT, and it is currently the best known upper extremity treatment for stroke survivors with mild impairment.

As mentioned above in 1.3.1, based on the possible neural mechanisms which support the effectiveness of bilateral movement training for upper extremities rehabilitation, bilateral movement training has been investigated as a potential rehabilitation intervention. Bilateral movement training is a nonspecific implementation for a number of different training techniques which use both limbs to complete rehabilitation trainings. Researchers have argued that it is important to include bilateral movement training, even though patients primarily perform the unilateral movement training (McCombe Waller and Whitall, 2008). They also indicated that, in comparison to unilateral training, bilateral training is suitable for treating stroke survivors with minimal, moderate and severe arm impairment.

Bilateral movement training

We reviewed above the effectiveness of bilateral movement training for upper extremities rehabilitation and three possible neural mechanisms which supported the bilateral effects. Bilateral training basically consists of a number of different therapeutic strategies which use both limbs to complete rehabilitation training.

Here, we will introduce several bilateral movement trainings which were argued by many researchers. At first, we will discuss several bilateral movement trainings which have been implemented as post-stroke rehabilitation trainings in the conventional physical therapy based on their evidence of efficacy; bilateral isokinematic training (BIT), bilateral mirror therapy. Additionally, after that, Device-assisted bilateral trainings, which are the most interested part for us, and bilateral priming will be discussed.

Bilateral isokinematic training (BIT)

The bilateral isokinematic training consists of symmetrical movements where both arms perform unassisted movements (Mudie and Matyas, 2000). In an attempt to exploit the well-established systematic bias towards spatial and temporal synergy, 'symmetry constraint', both upper extremities are used symmetrically to perform rehabilitation tasks. According to Cunningham et al. (2002), the interlimb coupling dynamics which reveal during bilateral movement training produce more similar parameters between the two limbs and, thus, enhance performance of the affected limb. Mudie and Matyas (2000) examined the effect of BIT. Twelve subjects trained in a unilateral movement training condition before shifting to a bilateral one. After switching to BIT, the subjects demonstrated improved performance in the kinematic assessment.

Cauraugh and Kim (2002) examined the implication of e-stim(electrical stimulation) in BIT for mildly impaired, chronic stroke subjects. The subjects were divided to the three groups: (1) a control group (training in unilateral wrist

extension exercises without stimulation); (2) a unilateral training group (wrist exercises augmented with e-stim); and (3) a bilateral training group (wrist exercises augmented with e-stim). They found significantly increased performance in the box and block test score, decreased reaction times, and improved sustained muscle contraction capability in the bilateral training group.

Mirror therapy using bilateral movement training

Mirror therapy which is well-known as one of the bilateral movement training has also shown an effectiveness for the upper extremities rehabilitation (Stevens and Stoykov, 2004; Yavuzer et al., 2008). In mirror therapy, a mirror is set in the saggital plane where the subject views the unimpaired arm as if it were the impaired one through the mirror. Mirror therapy can be performed in the bilateral movement condition where the impaired arm is out of view behind the mirror. The subject is asked to move his impaired hand at the same time as the unimpaired one. Stevens and Stoykov (2004) suggested one possible rationale for the success of this mirror therapy which is viewing the unimpaired arm provides a successful movement experience, similar to the image training, beyond what could otherwise be achieved in impaired one.

Yavuzer et al. (2008) examined the effect of bilateral mirror therapy by comparing a control group which performed sham mirror therapy. In the sham (i.e. non-reflecting side of) mirror therapy, the subjects performed in same bilateral movement condition while viewing the sham mirror. Functional independence measures between the groups revealed the significant improvement in favor of

mirror therapy with bilateral movement training.

Device-driven bilateral movement training

Many bilateral studies use a device which provides varying levels of assistance to the paretic arm to help complete a rehabilitation task such as symmetrical or asymmetrical movements more efficiently. One possible advantage of a device is that the stroke patients can practice many repetitions of rhythmic movement without requiring the full attention of a therapist. Another advantage is that the devices allow practice with varying levels of support including active, passive and active assisted movement (Stinear and Byblow, 2004; Hesse et al., 2005), and movement phases can be varied very precisely.

One group has invented a device named as the BATRAC which is associated with a protocol known as bilateral arm training with rhythmic auditory cueing (BATRAC). The BATRAC supports passive movement training. The subjects push the handles which placed on the nearly friction free slide away and then pull them toward the body. This protocol uses bilateral symmetrical and asymmetrical movement accompanied by rhythmic auditory cueing using a metronome to cue the patients. After 6 weeks of this BATRAC training, Whitall et al. (2000) reported significant improvement in strength, range of motion, and several assessment indices such as the Fugl-Meyer test of upper extremity motor function (FMUE) (Fugl-Meyer et al., 1975) and the scores on the University of Maryland arm questionnaire for stroke.

Bilateral training with rhythmic auditory cueing which previously described

by Whitall et al. (2000) was compared to dose-matched response therapy (DMRT) which used neurodevelopmental treatment techniques (Luft et al., 2004). The results indicated that improvement of the FMUE in six of the nine subjects in the BATRAC group, and no improvements in the DMRT group. All six subjects with FMUE improvements also had the increases in contralesional hemispheric activation as documented by fMRI.

Hesse et al. (2005) used a robotic device, known as the Bi-manu-track, to examine the effect of bilateral symmetrical therapy of the forearm in subjects in the subacute phase of stroke recovery. Here, the subject has the elbow joints fixed at about 90° and each hand grasps a handle and can be moved in one DOF. Two handle sets are available, one with a horizontal axis for forearm pronation/supination and one with a vertical axis for wrist flexion/extension movements. The Bi-manu-track group was compared to a group receiving e-stim of the wrist extensors. The Bi-manu-track group performed 850 bilateral symmetrical movement repetitions per session, whereas the e-stim group performed 60–80 wrist extension movements, if it is able, per session. There was significantly greater improvement in the bilateral group. The increased repetitions per session in the bilateral group might have accounted for some of the difference. Although the nature of the two treatments does not allow a fair comparison, the change in FMUE scores for the bilateral group (average was 16.7) is one of the largest reported in the literature.

Stinear and Byblow (2004) examined changes in measures of motor function and cortical activity using TMS following a combination of active and passive

bilateral training (APBT). The participants were in the subacute or chronic phase of stroke recovery. Subjects trained on a simple device, the 'Rocker', which coordinated active wrist movement of the unimpaired arm with passive movement of the impaired one. The subjects were assigned either to symmetrical or asymmetrical bilateral training, and practiced continuous wrist movement for one hour per day at a preferred frequency (approximately 1.2 Hz). After training, the results from the TMS evaluation included a decrease in the cortical excitability of the contralesional hemisphere (decreased cortical map volume) coinciding with significant improvement on the FMUE in five out of nine subjects.

Bilateral priming

Stinear et al., (2008) firstly reported that 'bilateral priming' study recently attracted a lot of attention as another bilateral protocol, where induces cortical excitability prior to motor practice. The bilateral movement is used as preparation for the brain prior to motor practice of unilateral or bilateral functional tasks. Bilateral priming, which consisted of APBT via the 'Rocker' device described on the previous paragraph, was provided to subjects for 10-15 min prior to performing tasks requiring hand dexterity. A control group performed the hand tasks alone. Both groups improved on the FMUE and had increases in cortical excitability in the ipsilesional hemisphere at post-treatment. However, unlike the control group, the bilateral priming group continued to improve (at follow-up) on the behavioral measures.

1.3.3 Neural Crosstalk

In this passage, we will discuss a neural crosstalk is the basis of interlimb coupling dynamics. A common assumption of bimanual coordination is that facilitation and interference effects emerge because of interhemispheric crosstalk. (Cardoso de Oliveira, 2002, see Figure 1.3) argued that there are at least two levels of the central nervous system at which neural crosstalk can occur.

High-level crosstalk is the result of transfer of abstract movement parameters such as slant, orientation, amplitude, and so on between the cortical hemispheres
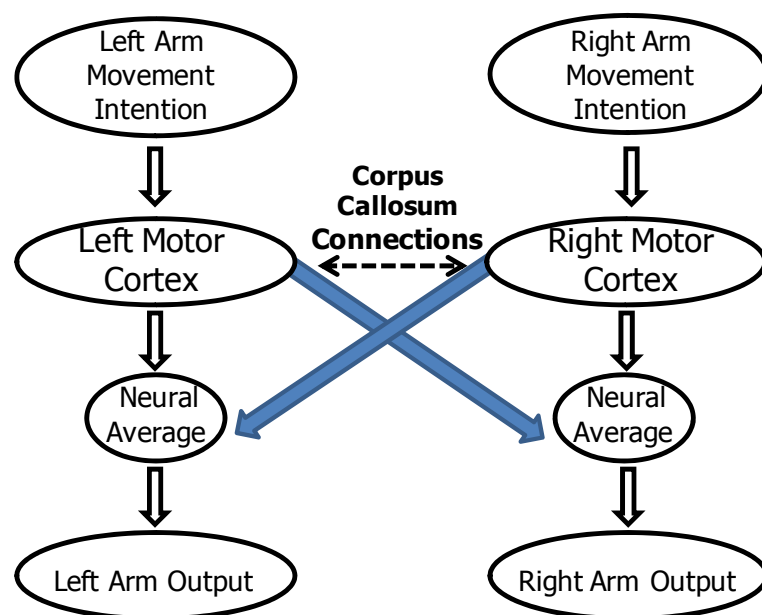
Figure 1.3 Movement intention model displaying two levels of crosstalk: (a) high level interactions between the left and right motor cortices via the corpus callosum; (b) low level subcortical interactions. The neural average signal for each arm is a consequence of the multiple interaction levels, and these interactions may cause the final efferent outputs to be more similar than originally planned. Figure modified from Cardoso de Oliveira (2002).

via callosal connections. The supplementary motor area (SMA) and premotor cortices have dense interhemispheric connections via the anterior portion of the corpus callosum and the parietal cortices via the posterior portion (Marconi et al., 2003).

Secondly, low-level neural crosstalk can occur in the subcortical area during the execution of movements that is downstream from the specification of abstract movement parameters. As reviewed in section 1.3.1, since there are corticospinal pathways do not cross at the pyramidal decussation in the brain-stem (ipsilateral corticospinal pathway), approximately 10~20% of the fibers remain uncrossed and project to the distal extremities in the ventral corticospinal tract (Kuypers, 1982, Lacroix et al., 2004). Based on the neural mechanism, ipsilateral corticospinal pathway, when bilateral symmetrical movements are performed, inputs to ipsilateral and contralateral pathways are consistent in reinforcing the coupling between the limbs.

1.3.4 Bilateral transfer

Bilateral transfer is an aspect of the transfer of learned skill and sensory or motor information on one side of the body to the other side. This transfer of information can occur normally in human via corpus callosum which connects both cortical hemispheres as shown in the Figure 1.4. Thus, a blindfolded human split-brain patient cannot, for example, replicate with the fingers and hand of his one side a complicated posture an experimenter imposes on the fingers and hand

of his other side (Sperry et al., 1969).

Since based on the bilateral transfer aspects, learning of one upper extremity can be affected by the results of the other upper extremity's learning and conditioning, the understanding of bilateral transfer aspects can provide insight into planning bilateral movement training for upper extremities rehabilitation.

The majority of investigations of bilateral transfer are mainly conducted for determining the transfer direction, the effect of handedness and element of bilateral transfer; from right to left side of the body or vice versa, laterality and
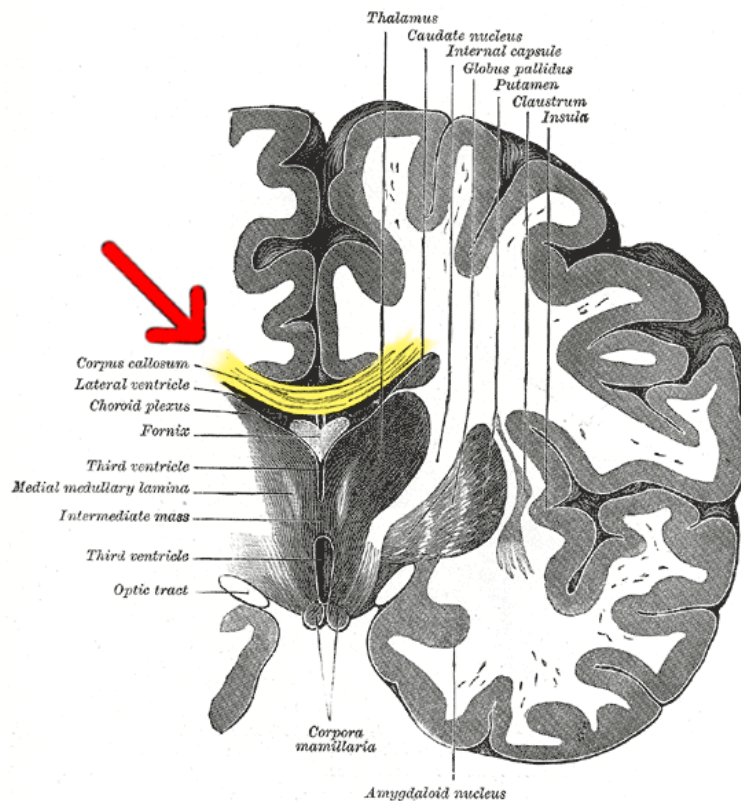
Figure 1.4 Corpus callosum(pointed out by an arrow) connects the left and right cerebral hemispheres and facilitates interhemispheric communication. It is the largest white matter structure in the brain, consisting of 200-250 million contralateral axonal projections. The copyright holder of this image release into the public domain (refer to http://en.wikipedia.org/wiki/Corpus_callosum).

sensory or motor information (Sainburg, 2002).

Criscimagna-Hemminger et al. (2003) 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.

To determine whether the direction of transfer depends on handedness, Wang and Sainburg (2006) examined the pattern of interlimb transfer following adaptation to 30° visuomotor rotations in left- and right-hander subjects (Sainburg and Wang, 2002). The results indicate unambiguous transfer across the arms. In terms of final position accuracy, the direction of transfer in left-hander subjects is opposite to that observed in right-hander subjects, such that transfer only occurred from the left to the right arm movements. This pattern of transfer is consistent with the hypothesis that asymmetry in interlimb transfer is dependent on differential specialization of the dominant and nondominant hemisphere/limb systems for trajectory and positional control, respectively.

Ausenda and Carnovali (2011) investigated the ability of bilateral transfer to facilitate the motor skill of the impaired upper extremity in stroke patients. In a randomized controlled trial twenty outpatient subjects were randomly assigned to either the bilateral transfer group or the control group. The rehabilitation protocol for bilateral transfer group consisted of the healthy hand movement of each patient to execute the nine hole-peg test 10 times a day, for three consecutive days,

and then tested the impaired hand with the same hole-peg test and with bimanual tasks. The control group was not trained with healthy hand but went through the same analysis. The homogeneity of the two groups has been proved. In the bilateral test group, they found that the execution speed of the nine hole-peg test with the impaired hand, after training the healthy hand, was on average 22.6% faster than the value recorded at baseline. The training had a positive effect on the execution of bimanual tasks. Meanwhile, no significant difference was found in the control group. The results indicated that bilateral transfer of motor skills facilitated the motor performance of the impaired hand. This study is the first clinical evidence that bilateral transfer of motor skills has positive effect to upper extremities rehabilitation after stroke. Thus, bilateral transfer aspect can be a new approach for planning the rehabilitation of stroke patients.

1.4 Summary

With the progress of the aging society, stroke or spinal cord injury patients who need rehabilitation are increasing steadily in the world. Recent evidence suggests that intensive therapy, longer training sessions per week and longer total training periods, improves movement recovery. However, such intensive therapy relies on the physiotherapist, where it is labor-intensive, time consuming and, therefore, expensive and lack of repeatability. To address these problems, many researchers have been focusing on the development of the robotic rehabilitation based on uses of robots and/or mechatronic devices, and various rehabilitation robotic systems have been developed.

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 extremity with disabilities. Although most stroke patients regain and recover the gait ability, 30%~66% of stroke survivors fail to regain functional recovery of the impaired upper extremity. Therefore, stroke researchers and physiotherapists are trying to search for more effective upper extremity rehabilitation protocol for regaining voluntary upper extremity movement. A current prominent rehabilitation protocol for upper extremities is bilateral movement training. Many activities of daily living such as driving a car, reaching for an object, 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. This provides a rationale

for the incorporation of bilateral movement training into upper extremities rehabilitation protocols.

The primary question for bilateral movement training is how the upper extremities interact with each other. Thus, the investigation of innate properties of the human(or healthy subject) such as interlimb coordination and bilateral transfer has been the subject of intensive research.

Robot-aided rehabilitation systems have clear benefit to freely construct various bilateral movement trainings which induce much more interactions between unimpaired and impaired upper extremities for effective rehabilitation therapy. Since robot-aided rehabilitation systems provide the mechanical assistance to patient's impaired upper extremity to help complete a desired movement by physical contact, sensory or motor systems to perceive a movement and resistive or assistive forces should be much more considered. Thus, we need to understand the relationship between left and right side of human sensory or motor system for planning more appropriate bilateral movement training.

1.4.1 Goals for the dissertation

The goal of this dissertation is to investigate the relationship between left and right side of human sensory or motor system for planning more appropriate bilateral movement training based on the robot-aided rehabilitation systems. The main idea is to find the exact therapeutic conditions that mediate functional motor recovery post-stroke caused by much more interactions between upper extremities.

Since the motor recovery based on task-oriented therapies is achieved by the sensory nervous systems, the understanding of sensory nervous systems can be helpful in the planning of rehabilitation therapies. The sensory nervous systems to perform the rehabilitation training are fixed by depending on the task-oriented therapies. The study of the sensory systems can provide insight into planning new rehabilitation trainings. To achieve this goal, we are focusing on the sensory system, especially, proprioception and force perception. Figure 1.5 shows the outline of this thesis and reveals the relation of three chapters from chapter 2 to chapter 4.

Figure 1.5 Outline of this thesis.

One type of the sensory system, proprioception is generally believed to control the awareness of joint angle, motion and force (Farrer et al., 2003). Thus, the proprioception plays an important role in the control of goal-directed movements which is the most common physical therapy. Thus, in chapter 2, we firstly discussed the bilateral transfer of proprioception in active and passive conditions.

And also, in robot-aided rehabilitation systems, according to the rehabilitation processes, 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 elements for robot-aided rehabilitation which was considered in chapter 3.

The bilateral transfer of sensory information is one kind of the interactions between upper extremities. Thus, through the evaluation of the bilateral transfer of the proprioception and force perception in chapter 2 and chapter 3, the therapeutic conditions which cause much more interactions between upper extremities could be found in chapter 4. We hypothesize that the therapeutic conditions actively occur the bilateral transfer will induce the neural plasticity for the recovery and reorganization of lost motor function.

The primary novel contributions of this dissertation are:

1. Investigation of bilateral transfer of proprioception

In chapter 2, we discuss the bilateral transfer of the proprioception which is important to perceive a movement such as predefined trajectory for rehabilitation. The effect of one upper limb's proprioception on the movement of the other upper limb is verified by the differences in reproducing performance during both active and passive guidance conditions of the robot manipulators. Active and passive guidance-reproduction based bimanual tasks are used for the experiment; in these the subject is asked to hold both right and left knobs installed at the end-effectors of two robot manipulators. 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.

2. Investigation of bilateral transfer of force perception

The objective of chapter 3 is to investigate the bilateral transfer of force perception. Particularly, the transfer performance according to the magnitude and direction of force was verified. Force perception-regeneration bimanual task in isometic condition without the movement of upper extremities was used in order to focus on only force perception. The results indicated that the bilateral transfer of force perception is the function of the simultaneity and the magnitude of force and the bilateral transfer of force perception actively occurs regardless of the direction of force.

3. Planning of bilateral movement training

Chapter 4, using the results of the previous two chapter's studies, focuses on the planning of bilateral movement training which can induce the more interaction between upper extremities.

Chapter 2

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

2.1 Introduction

After stroke, pathways in the brain are depleted because of damaged neurons. Intensive therapy, longer training sessions per week and longer total training periods, improved movement ability of the hand and arm after stroke according to the studies of the upper extremity (Taub et al. 1999). This improved movement

ability arose at least in part from cortical reorganization. It has been hypothesized that intensive therapy facilitates rewiring of the brain by the neural plasticity, with undamaged cortical areas assuming control functions previously allocated to damaged ones (Liepert et al., 2000). This neural plasticity has major implications for the types of rehabilitation training administered post-stroke. Since, based on behavioral and neurophysiological mechanisms, bilateral movement training can induce much more interactions between unimpaired and impaired upper extremities to facilitate the neural plasticity, bilateral movement training has shown great promise in expending progress toward stroke recovery in upper extremities. However, the critical therapeutic parameters underlying bilateral effect have not been clarified.

The goal of this dissertation is to find the exact conditions that would cause much more interactions between upper extremities in order to plan effective bilateral movement training for robot-aided rehabilitation systems. As a first step toward this goal, we investigated the bilateral transfer of proprioception based on a property of muscle spindles. This chapter describes why we choose the proprioception among the sensory system, and active and passive guidance-reproduction based bimanual tasks were used to evaluate the bilateral transfer of proprioception. 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.
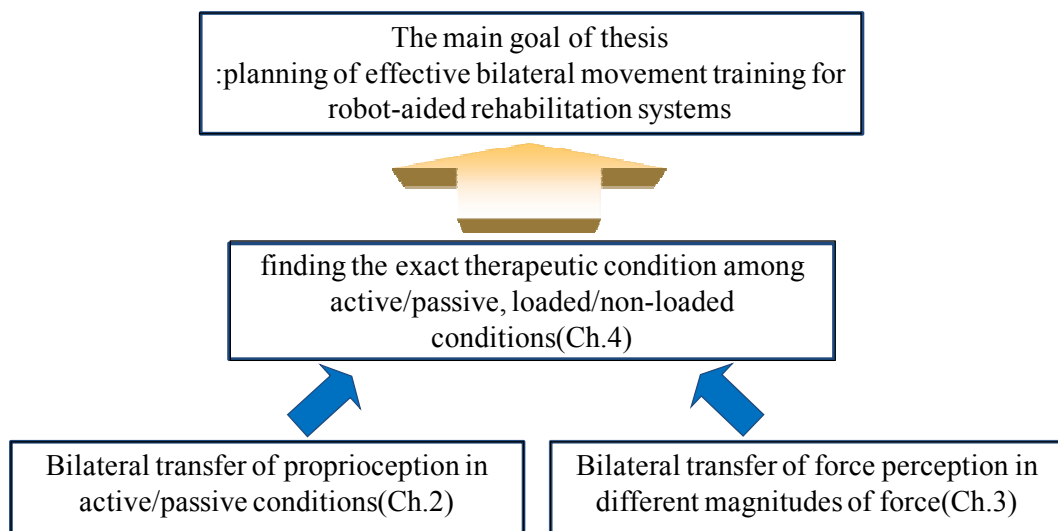
2.2 Motivation and Background

2.2.1 Bilateral transfer of proprioception

One type of the sensory system, proprioception is generally believed to control the awareness of joint angle, motion and force (Farrer et al., 2003) and to play an important functional role in the control of goal-directed movements which consists of the most common physical therapy (Jeannerod et al., 1991). Research results from the investigation on the role of proprioception suggest that before the initiation of movement, proprioceptive information about body and limb position relative to movement goal forms the basis for the programming of the motor commands. During movement, proprioceptive input on limb progression is used to regulate movement by modulating the motor commands. Finally, towards the end of movement completion, proprioceptive feedback is used to evaluate accuracy and quality of movement, enabling final corrections to be performed (Ghez et al., 1991, Park et al., 1999). As proprioception plays an important role in motor control, its evaluation and treatment is relevant to physical rehabilitation (Hasam et al., 1992, Dannenbaum et al., 1993, McNair et al, 1996). 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 (Carey et al., 1993). For an 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 guided joint position and movement with same extremity (Carey et al., 1996). Therefore, it is reasonable to investigate the relationship between proprioceptions of the left and right arms for planning bilateral movement training. Additionally, due to the handedness, the two upper limbs have an asymmetrical neural organization in the human motor system (Sainburg, 2002). Therefore, to investigate the relationship between upper extremities, the effect of handedness also should be considered.

2.2.2 Muscle spindles and proprioception

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 of muscle length, position and tension.
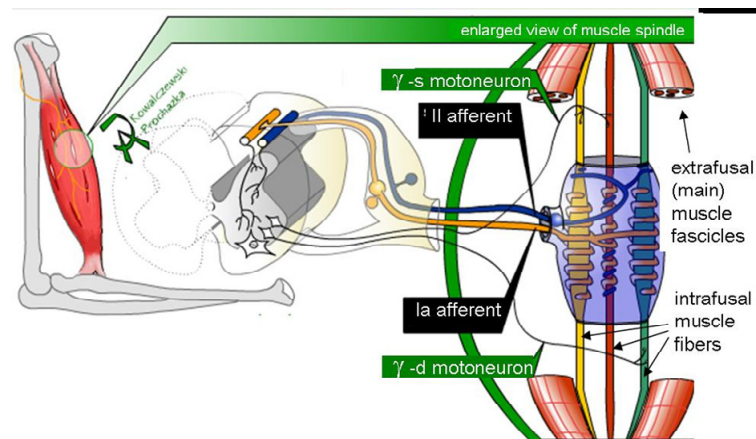
Figure 2.1 Basic organization of muscle spindle. These sensory organs lie in parallel with the extrafusal muscle fibers and are therefore adapted to monitor muscle length changes. The copyright holder of this image release into the public domain (refer to http://en.wikipedia.org/wiki/Muscle_spindles#cite_note-0).

The role of the muscle spindles as comparators for the maintenance of muscle length is important during goal-directed voluntary movements. Figure 2.1 shows the basic organization of a muscle spindle; typical position of muscle spindles in a muscle (left), neuronal connections in spinal cord (middle) and its expanded schematic (right). The muscles fibers of the muscle spindles are called intrafusal fibers while those of the main body of the muscle are the extrafusal fibers. The spindle is a stretch receptor with its own motor supply consisting of several intrafusal muscle fibers. The motoneurons innervating the intrafusal fibers are called as gamma-motoneurones (γ-motoneurones, or fusimotor neurons) to distinguish them from the α-motorneurones, which innervate the extrafusal fibers. Gamma motoneurons activate the intrafusal muscle fibers so that sensitivity of muscle spindle to changes in muscle length is maintained by changing the resting firing rate and stretch-sensitivity of the afferents. This is known as fusimotor control (or action) (Pocock et al., 2009). The simultaneous activation of extrafusal fibers and intrafusal fibers is called alpha-gamma co-activation and continuously readjusts the sensitivity of muscle spindles as the muscle contraction (Ribot-Ciscar et al., 2009). Since the muscle spindles are subject to central fusimotor control (Proske et al., 2000), the sensitivity of muscle spindle is varied by muscle activity patterns and commands in passive and active movements (Laufer et al., 2001). Therefore, many researchers apply this characteristic of muscle spindle to their experimental method when they investigate the characteristics or role of proprioception in motion (Proske et al., 2000).

2.2.3 The object of this chapter

The objective of this chapter 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 has been 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. To verify the effect of simultaneity on the reproducing performance, non-simultaneous and simultaneous tasks were used in this study. 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 at the same time or after guidance in simultaneous and non-simultaneous task, respectively. 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

2.3 Methodology

2.3.1 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. Before experiments began, the subjects read and signed an 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 (Oldfield, 1971).

2.3.2 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
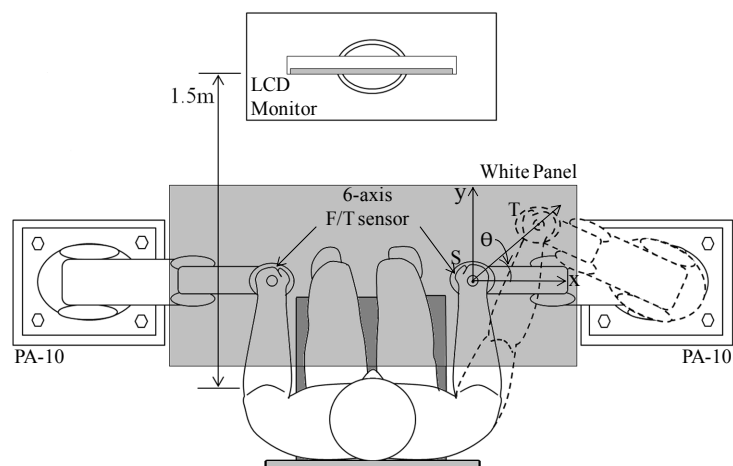
Figure 2.2 Top view of experimental setup

force/torque sensors (NITTA corporation) were attached between the robot end-effector and the knob. The motions of manipulator were restricted on the horizontal plane (xy plane in Figure 2.2). The monitor was set 1.5 meters in front of the subjects who sit on the chair. During the experiments, the subject was asked to concentrate on the monitor.

In the active guidance condition, the positions with respect to x and y of the end-effector were defined as the output of the second-order dynamical system described by (2.1), i.e. impedance control. This equation is well-established in the field of robotics and human robot interaction (Cheah et al, 1998).

$$F = M\ddot{z} + D\dot{z} + Kz \qquad\qquad (2.1)$$

The inertia (M), viscosity (D) and stiffness (K) were 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 might move the robot end-effector with sufficiently small muscle force. The position x and y were calculated based on the (2.1), 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 (2.1) for calculating the x position, and y position was obtained by substituting y-axis force into (2.1). 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 contrast, for the passive guidance condition, the robot guided one hand of the subject from the start

point (S) to the target point (T), as shown in Figure 2.2, 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 was 20cm, and the angle (θ) from the x-axis to the straight line trajectory was 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, a white panel was 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 50Hz for evaluating 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 desired hand trajectory with various arm configurations to reach a specific position, people typically generate a reaching movement with natural motion trajectory based on minimizing the magnitude of total work done by joint torques. Thus, the joint trajectories of typical unrestrained movements tend to be consistent both within and across subjects (Kang, et al., 2005). In this 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 Figure 2.2.

2.3.3 Targets

Two knobs are 40cm apart from each other. Figure 2.3 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
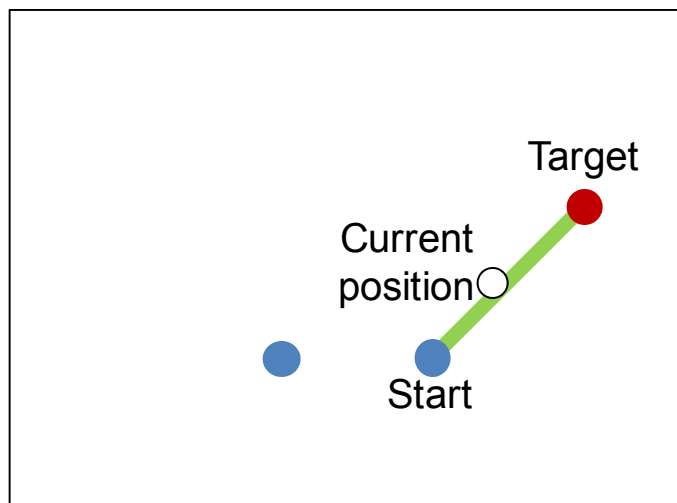
Figure 2.3 Example of experimental display

respect to the sagittal plane of the subject. A small white circle was displayed for the hand position of the subject; and the target and start points were displayed as small red and blue circles, respectively. In both active and passive guidance modes, when the black circle is at the target point, a green 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.

2.3.4 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 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 (Makiko et al., 2000). 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 (Mark et al., 1997). Therefore, 20 cm was confirmed 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 (Pocock et al., 2009). However, according to Walsh et al. (Walsh et al., 2004), the sensitivity of muscle spindle is affected by muscle fatigue. To avoid this effect, a preliminary experiment was performed to find the coefficients M, D and K in Eq. (1) and to determine the magnitude of the impedance so that the subject could move the robot end-effector with sufficiently small muscle force.

2.3.5 Experimental conditions and procedures

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 movements of the controlled position in the monitor.

TABLE 2.1

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

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

The 4 experimental conditions of non-simultaneous task shown in Table 2.1 were used to compare the subject's reproducing performances. The subject was asked to reproduce the mirror-symmetrical motion with respect to the motion of the contra-lateral upper limb after the guidance. 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 C2 and C4 the robot guided one hand of the subject in trajectory control mode, while in the conditions of C1 and C3 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 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.

In the simultaneous task, the experimental conditions were same as the non-simultaneous task, but, the subject performed the guidance and reproduction mode at the same time. The time duration of robot movement in passive guidance mode and sequence of target presentation was same to the non-simultaneous task.

Passive guidance condition

The experimental procedure for the passive guidance conditions, C2 and C4, can be carried out as follows. The Figure 2.4 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 Figure 2.4

Step 1: One hand (left hand in C2 and right hand in C4) 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 Figure 2.3. It
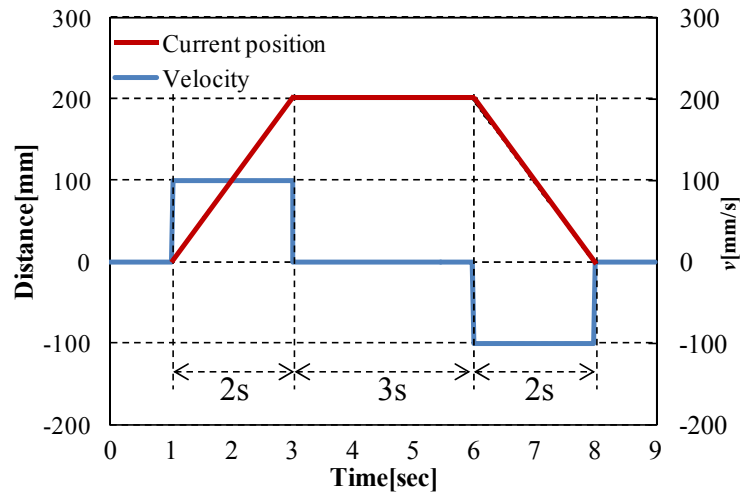
Figure 2.4 Current position and velocity of end-effector in passive guidance.

takes about 2 seconds to reach the target point from the start point as shown in the Figure 2.4

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 (right hand in C2 and left hand in C4) 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, the process was terminated; otherwise, the next target point is set in the monitor and Step 1 follows.

Active guidance condition

For the active guidance conditions, C1 and C3, 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. Figure 2.5 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.
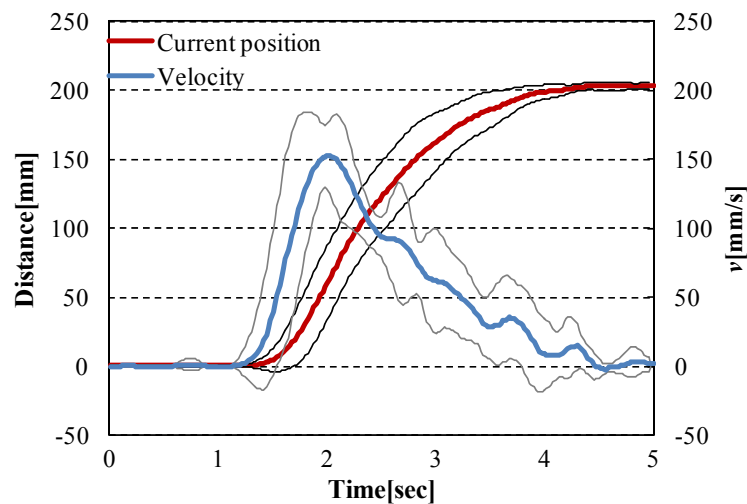
Figure 2.5 Mean values of current position and velocity of one subject for 15 trials. Thick lines show changes in the mean position and velocity, and thin lines indicate the standard deviation for these means

Step 1: The subject moves one of their hands (left hand in C1 and right hand in C3) 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).

15 trials were performed in each condition of non-simultaneous and simultaneous task. Each condition of Table 2.1 was performed once by each subject. In theory, iterative tasks may be affected by learning and order effects. To avoid this effect, the order of the experimental conditions for each subject was randomly determined, and each subject take a 10 minute break between conditions in the experiment. Note that through comparison between C1 and C3 the active guidance condition and between C2 and C4 the passive guidance condition, the effect of handedness can be investigated.

2.3.6 Data measurement 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. Figure 2.6 shows four variables used evaluate the reproduction performance: E, S and T are the positions of the end
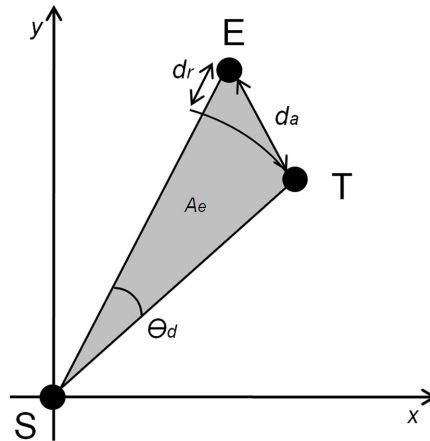
Figure 2.6 Illustration of dependent variables in the case of the right arm

point controlled by the subject, the position of the start point, and the position of the target point, respectively; da is the absolute distance between E and T; and dr 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 θd is the angular difference between E and T. The error area (Ae) was also calculated as shown in the Figure 2.6, which is defined as the integral of the difference between the straight line to the target and the actual trajectory.

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.).

2.4 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 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.

TABLE 2.2
EXPERIMENTAL RESULTS OF NON-SIMULTANEOUS TASK

Conditions	Absolute distance(mm)	Range (mm)	Angular deviation(^{0})	Error area (mm^2)
C1	28.41	23.87	-1.40	1026.87
(AG-RR)	(10.78)	(12.27)	(3.38)	(866.45)
C2	34.01	29.48	-2.34	2111.33
(PG-RR)	(12.15)	(12.52)	(5.43)	(1328.40)
C3	60.55	46.27	-10.71	4079.51
(AG-RL)	(22.22)	(22.53)	(4.11)	(1639.16)
C4	71.96	55.58	-11.54	6183.25
(PG-RL)	(24.72)	(24.36)	(4.57)	(2466.15)

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

In order to verify how proprioception influences on the reproducing performance in the contral-lateral 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 2.2 shows the average values and the

standard deviations of the evaluation variables for each condition of the ten subjects in non-simultaneous task. The results of the paired-samples t-test are discussed in the next sections.

2.4.1 Comparison between the active and passive conditions

Figure 2.7 shows the actual tracking trajectory 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 trajectory was 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 2.2, the comparison between the active and passive guidance conditions (C1 and C2 for right hand reproduction mode and C3 and C4 for left hand reproduction mode) indicates that for both left and right hand reproduction modes, more accurate reproducing performance was obtained

(a)passive guidance condition   (b)active guidance condition
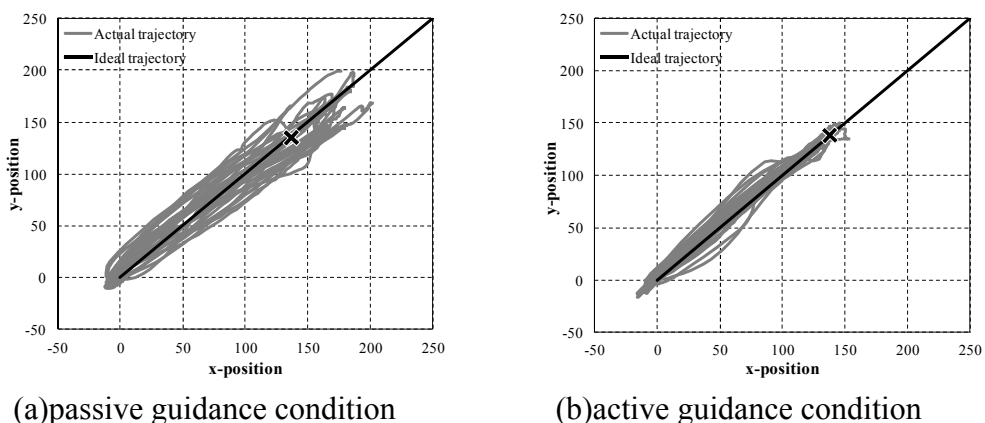
Figure 2.7 Tracking trajectory of one subject in active and passive conditions for left-guidance-right-reproduction mode(x is the target point).

when the proprioceptive sensory feedback was acquired from the active guidance condition (C1 and C3).

Figure 2.9 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. In the statistical test, the p-value means the probability of an event or outcome, specifically it indicates the probability of rejecting the null hypothesis when it is true. Thus, the existence of the significant difference between two groups is evaluated by the p-value in statistical analysis; typically, if p is less than 0.05, there is significant difference between two groups. Note that the p-values of range and angular deviation between C1 and C2 (the graphs in the upper left of b and c in Fig. 2.9) 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.

We compare the statistical results of unimanual tasks which were conducted in Laufer et al. (Laufer et al., 2001) and left-guidance-right-reproduction bimanual tasks (C1 and C2) in this study for both active and passive conditions although the subjects who participated in Laufer et al. (Laufer et al., 2001) and present study were different; 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. 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 C1 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 the 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 C2 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. 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.

2.4.2 Comparison between the left- and right-reproduction

To investigate the effect of handedness, we also compared the results of left- and right- reproduction modes. Figure 2.8 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 trajectory was nearer the ideal trajectory and the positions of the end point which controlled by the subject was closer to the target point than in right-guidance-left -reproduction mode. Based on the results shown in Table 2.2, the comparison between the left- and right-reproduction modes (C2 and C4 in the passive guidance condition and C1 and C3 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

(a) left-reproduction mode   (b)right-reproduction mode
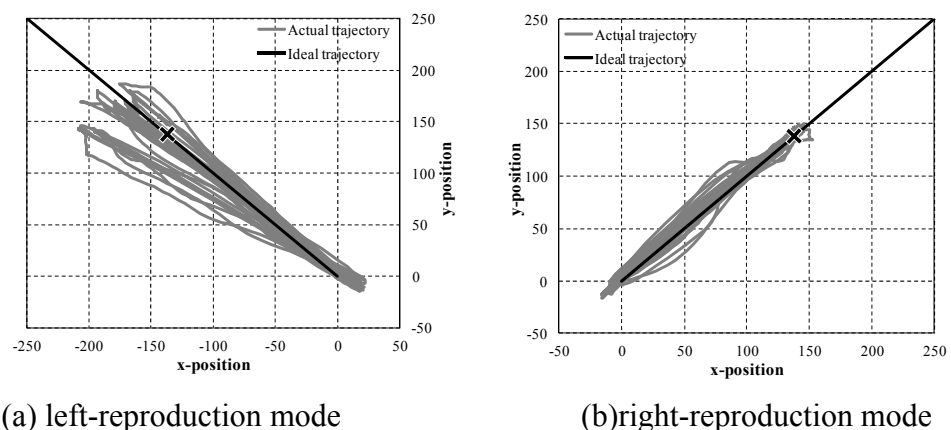
Figure 2.8 Tracking trajectory of one subject for left-reproduction and right-reproduction modes in active guidance condition(x is the target point).

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. The lower two graphs of each variable in Figure 2.9 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.
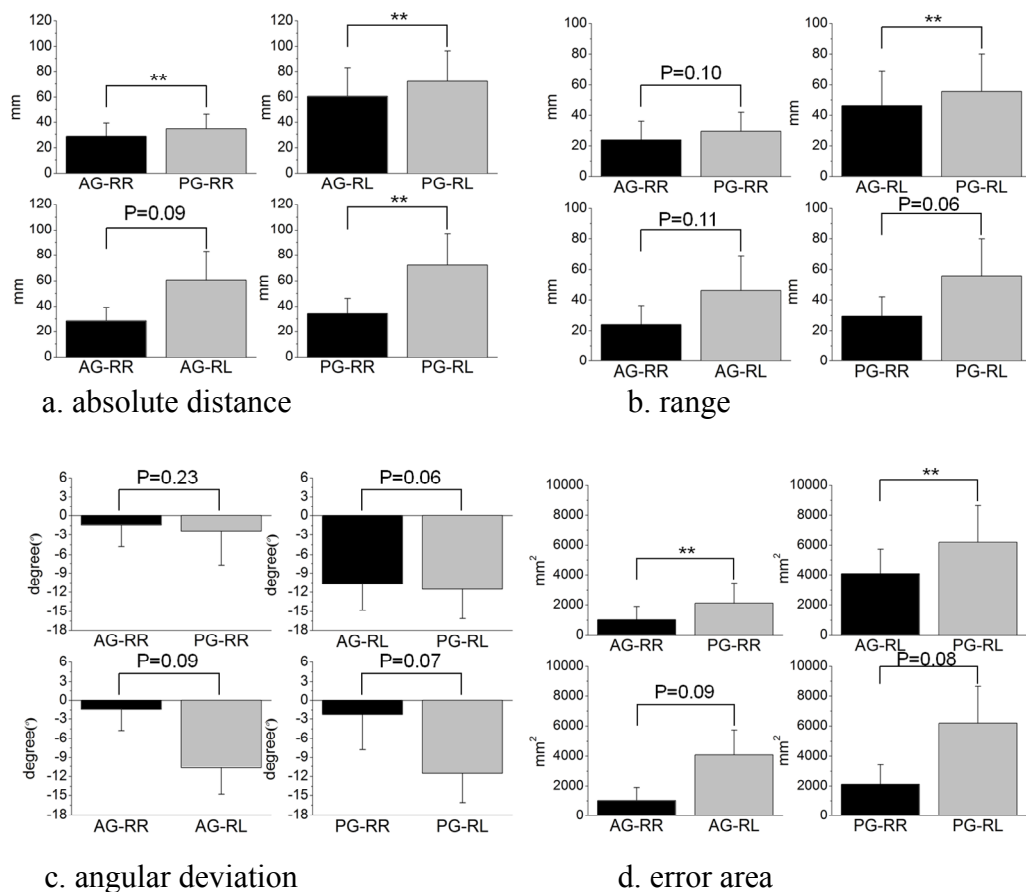
Figure 2.9. Mean of ten subjects for the four variables: absolute distance, range, angular difference and error area from a to d, respectively. The values of the paired-samples t-tests are shown in the figures, where ** means p<0.05 or the p-value is shown.

2.4.3 Comparison between the non-simultaneous and simultaneous

Table 2.3 shows the average values and the standard deviations of the ten subjects in simultaneous task. The more accurate reproducing performance was revealed in active guidance condition for both left and right hand reproduction modes. To verify the effect of simultaneity on the reproducing performance, we compared the experiments results between non-simultaneous (Table 2.2) and simultaneous (Table 2.3) task in all conditions.

TABLE 2.3

EXPERIMENTAL RESULTS OF SIMULTANEOUS TASK

Conditions	Absolute distance(mm)	Range (mm)	Angular deviation(^{0})	Error area (mm^2)
C1 (AG-RR)	30.83 (16.73)	20.57 (12.23)	-4.46 (6.07)	1953.87 (2408.57)
C2 (PG-RR)	33.01 (17.58)	28.59 (27.96)	-3.71 (0.70)	2398.12 (255.15)
C3 (AG-RL)	27.11 (9.03)	9.90 (14.58)	-1.97 (5.70)	1877.45 (952.41)
C4 (PG-RL)	39.18 (8.99)	28.90 (6.84)	-1.21 (7.29)	3831.49 (3129.33)

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

In the case of the right guidance and left reproduction conditions (C3 and C4), the result of simultaneous task has been demonstrated better reproducing performance than the result of non-simultaneous task in all evaluation variables. In the simultaneous task, since the subjects performed the guidance and

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reproduction modes at the same time the reproducing performance could be better than the non-simultaneous task which should exists a time delay between the guidance and reproduction modes. However, the comparison result of simultaneous and non-simultaneous tasks in the left guidance and right reproduction condition (C3 and C4) showed that almost same reproducing performance in active and passive guidance modes. Even though, a time delay was existed in the non-simultaneous condition, the time delay could not effect to the reproducing performance. This result also revealed that the direction of bilateral transfer was better from left to right for the right handed subjects.

2.5 Discussion

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 (Cauraugh, 2005). 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 (Swinnen, 2002). 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 (Laufer et al., 2001) Additionally, according to the comparison results between unimanual tasks which were conducted in Laufer et al. (2001) and bimanual tasks in this study, reproducing performances of unimanual tasks were more accurate than in bimanual tasks for both active and passive conditions. These results indicated the effect of bilateral transfer on the proprioceptive sensory feedback and the difference hand in the guidance and reproduction modes during unimanual and bimanual tasks: ipsilateral hand and contra-lateral hand, respectively.

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 (Yamamoto et al., 2005). 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. 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., Since the efferent central signals for reaching movements are likely to be absent in the passive guidance condition, the subject is able to use only proprioceptive signals from guided hand for the movement reproduction. Thus, the more accurate reproducing performance could be obtained in active guidance condition.

According to the research of Oliveira (Oliveira, 2002) 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. These high and low level cross talks have been identified that they more actively respond to simultaneous movement of the two upper extremities. Therefore, the result of simultaneous task which subject performed the guidance and reproduction mode at the same time has been demonstrated better reproducing performance than the result of non-simultaneous task. 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 (Piron et al., 2005). 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.

2.6 Conclusion

In this chapter, we investigated the effects of proprioception and handedness based on spatial bimanual coupling. The results of this chapter indicated that the bilateral transfer of proprioception was actively caused in the active guidance condition of both simultaneous and non-simultaneous conditions. The direction of bilateral transfer of proprioception was better from the left (non-dominant) to the right (dominant) rather than the opposite. 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.

Chapter 3

Bilateral Transfer of force perception in Force Perception-Regeneration Bimanual Task

3.1 Introduction

Robot-aided rehabilitation systems provide the mechanical assistance to patient's impaired upper extremity to help complete a desired movement by supporting the desired movement trajectory or the desired force. For the assistance, patient and robot-aided rehabilitation systems interact with each other by physical contact. Therefore, in the case of the robot-aided rehabilitation, human sensory systems to perceive a movement and resistive or assistive forces provided by

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robot-aided rehabilitation systems should be much more considered. Thus, to plan appropriate bilateral movement trainings induce much more interactions based on the robot-aided rehabilitation system, we need to understand the relationship between left and right side of sensory system; proprioception and force perception. In chapter 2, we discussed the bilateral transfer of the proprioception which was important to perceive a movement such as predefined trajectory for rehabilitation. In this chapter, we focus on the bilateral transfer of force perception to investigate the relation between left and right side of upper extremities.

3.2 Background and Motivation

3.2.1 Studies of bilateral transfer and force perception

According to the rehabilitation processes, in robot-aided rehabilitation systems, robots commonly resist the movements of upper extremity or compensate the gravity force on the upper extremity itself. Therefore, force perception is important factor which should be considered. The bilateral transfer of sensory information is one kind of the interactions between upper extremities. Thus, through the evaluation of the bilateral transfer of the force perception, the conditions which cause much more interactions between upper extremities can be defined. We hypothesize that the conditions actively awaking the bilateral transfer will induce the neural plasticity for the recovery and reorganization of lost motor function.

Numerous psychological research studies have explored the bilateral transfer of spatial and temporal perception (Cook, 1933). Studies on bilateral transfer have usually shown an advantage of previous practice with the homologous contralateral limb in tasks such as drawing/writing (Parlow & Kinsbourne, 1989; Thut et al., 1996), tactual recognition (Parlow & Kinsbourne, 1990; Sathian & Zangaladze, 1998), pointing under displaced vision (Elliott & Roy, 1981), pursuit tracking (Hicks, Gualtieri, & Schroeder, 1983), mirror tracing (Cook, 1933a, 1933b), and maze tracking (Milisen & Riper, 1939; Wieg, 1932).

Recently, since studies of bilateral transfer can provide insight into planning

bilateral movement training for post-stroke rehabilitation, studies of bilateral transfer have been attracting a lot of attentions from various research fields such as engineering and medicine. For examples, Teixeira et al., (Teixeira et al., 2003) examined the amount of bilateral transfer of force control in relation to symmetry conditions of force; symmetric force (SM), asymmetric force (AS), or a control condition (CO). The learning task consisted of launching a small cart across a metallic track way with dominant hand, after learning task, transfer task requiring a mirrored action with the contralateral hand was performed by SM and AS group, while the CO group had active rest. The results indicated that the SM group achieved significantly higher bilateral transfer of learning as compared to the AS group, which presented response variability similar to the CO group.

Although these studies of bilateral transfer have revealed an increased proficiency in performance with a resting upper extremity after practice with the contralateral homologous upper extremity, most of their experimental protocols were conducted with the combination of the sensory and motor system such as a movement of upper extremity. Thus, few investigations have provided information about what elements and conditions are effectively transferred to the contralateral side of the body. Therefore, in this chapter, we focus on the bilateral transfer of one element: force perception.

3.2.2 The object of this chapter

The objective of this chapter is to investigate the bilateral transfer of force

perception, particularly, the relationship between transfer performance and magnitude or direction of force. We suggest force perception-regeneration bimanual task in isometic condition without the movement of upper extremities in order to focus on only force perception; in these the subjects were asked to sit on the chair and grip right and left joysticks fixed on the two force/torque sensors which were installed on the rigid structures. In the perception-regeneration bimanual task, the subjects push or pull the joysticks. The applied forces to y-axis direction were measured by force sensors. In perception mode, the subjects generate predefined (target) forces with his one hand based on the visual feedback through LCD monitor. In order to evaluate the bilateral transfer of force perception, in regeneration mode, the subjects are asked to regenerate the same force which perceived on the contra-lateral upper extremity without visual feedback. There are two conditions; the non-simultaneous task and simultaneous task which the subjects are asked to regenerate the same force which perceived in perception mode after force perception and perform the perception and regeneration mode at the same time, respectively. The magnitude of force and direction of force perception/generation were used the parameters of two experiments.

3.3 Methodology

3.3.1 Subjects

Three 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.

3.3.2 Experimental apparatus

The experimental apparatus consisted of two 6-axis force/torque sensors (NITTA Corporation) were attached on the rigid structures as shown in the Figure 3.2. Two joysticks were adjusted to be apart from each other as same as shoulder width of each subject. The monitor was set 1.5 meters in front of the subject as
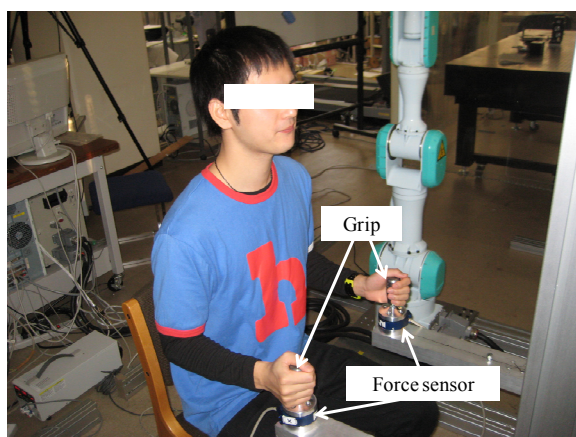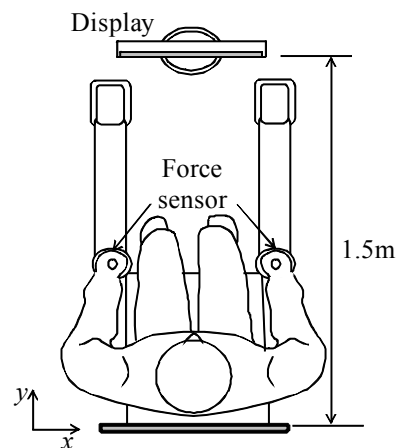
(a)Experimental environment   (b) Experimental layout

Figure 3.1 Experimental environment and layout

shown in the Figure 3.1. During the experiment, the subject was asked to concentrate on the monitor. The subject was asked to sit on the chair for gripping the joysticks with fifty percentage length of their upper limb. The height of 6-axis force/torque sensors was adjusted by the angle between upper arm and lower arm to be almost 90 degrees. The direction for force perception/regeneration was basically front direction from the body (y axis in Figure 3.1(b)).

In perception mode, the subject generated predefined (target) forces with his/her one hand based on the visual feedback which displays currently generating forces through LCD monitor. In order to evaluate the bilateral transfer of force
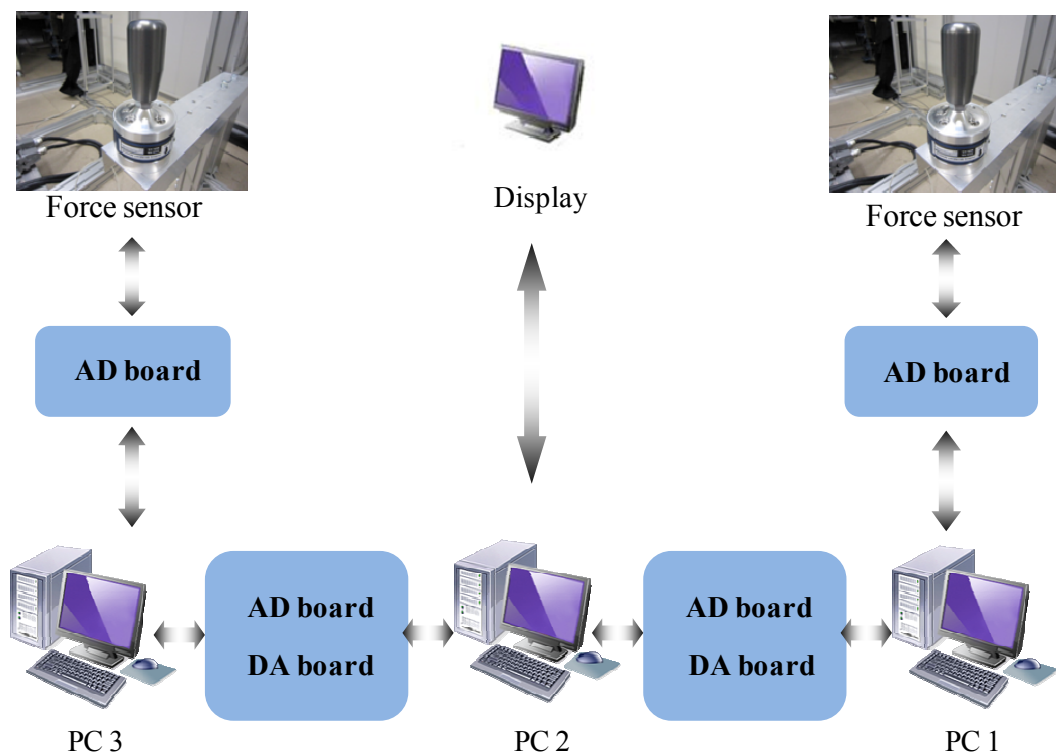
Figure 3.2 System compositions of experimental apparatus.

perception, in regeneration mode, the subject was asked to regenerate the same force with respect to the force perception of the contra-lateral upper extremity without visual feedback.

Figure 3.3 shows the example of experimental display when right-hand perception and left-hand regeneration in non-simultaneous task. A white controlled bar(hereafter, CB) located in the middle was displayed for the currently generating force of the subject only in the guidance mode; top and bottom side green bars showed a start point(hereafter, SP) and a target force(hereafter, TF), respectively. The small red circle showing the tracking point(hereafter, TP) moved from the SP to the TF and back to the SP in predefined time sequences, and guided the subject to perceive and regenerate the TF. Figure 3.4 shows an example of time sequence for movement of TP in the case of the TF bar, when a difference between TF and generating force is smaller than the five percentages of TF, the color of TF bar change to a red color to help guidance the subjects in making a TF more precisely. During the experiments, the generating forces of the
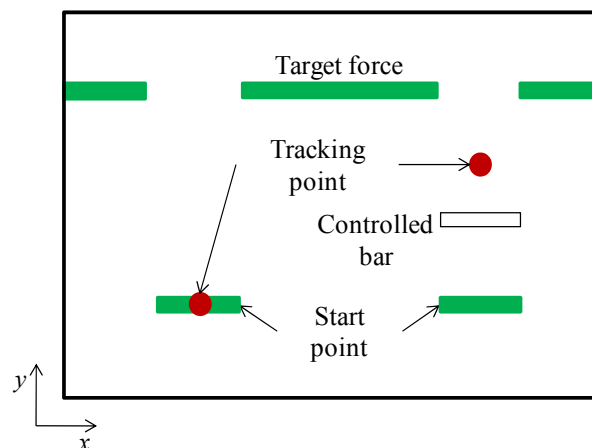
Figure 3.3 Example of experimental display
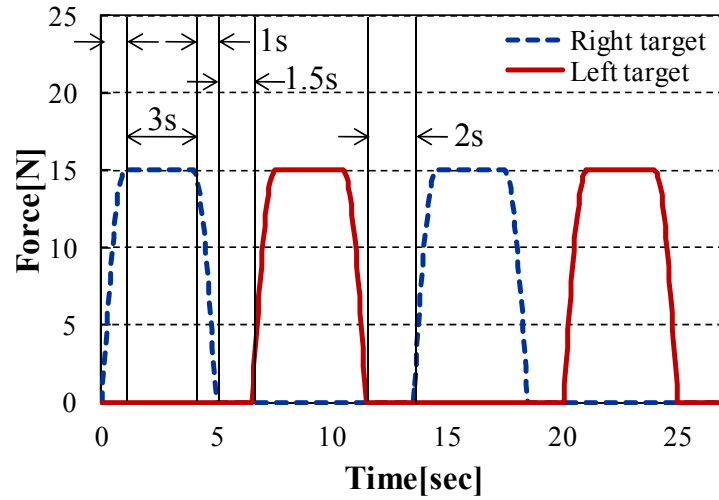
Figure 3.4 An example of target force signal in right-perception left-regeneration non-simultaneous task.

subjects were recorded with a sampling frequency of 20Hz for evaluation of the reproducing performance.

3.3.3 Experimental conditions and procedures

The subject sat on a chair that was located in midway between the two 6-axis force/torque sensors and held onto the left and right joysticks with their left and right hands, respectively. Before starting the main experiment, the subjects had test trials for 5 minutes to get used to the experimental environment, matching their force generation to those of the CB in the monitor.

Non-simultaneous task

In the non-simultaneous task, the subjects are asked to regenerate the same

force which perceived in perception mode after force perception. Figure 3.4 shows an example of target force signal in right-perception left-regeneration non-simultaneous task and it can be carried out as follows.

Step 1: the TP of perception side (right side in this example) moves from the SP to the TF. It takes 1 sec as shown in the Figure 3.4. The subject pushes the joystick to generate the force with his/her right hand, where the CB tracks the TP movement.

Step 2: After the TP reached the TF, the TP stops at the TF for 3 seconds. The subject is asked to generate a stable force which same to TF. At this time, the subject consider the generated force as perception force

Step 3: The TP returns to the SP with same time duration of Step 1. The subject stops to generate the force. This is the end of perception mode.

Step 4: After returning to the start point, the subjects wait for 1.5 seconds.

Step 5: the TP of regeneration side (left side in this example) moves from the SP to the TF, and return to the SP with same time duration and sequence from step 1 to step 3. In the regeneration side, the CB is not displayed. Thus, the subject is asked to regenerate the same force with his/her left hand based on the force perception in the perception mode.

Step 6: After the force regeneration mode, the subject wait for 2 seconds.

Step 7: After from step 1 to step 6, a repetition number is counted. If the repetition number is smaller than 10, the next TP is set in the monitor and Step 1 follows.

Simultaneous task

In the simultaneous task, the subjects are asked to regenerate the same force which perceiving force in perception mode at the same time. For the simultaneous task, we use the overlapped TP signal of both perception and regeneration side in Figure 3.4. Thus, the time duration and sequence of the TP presentation is same to the non-simultaneous task. The subject is asked to perceive and reproduce the force with respect to the TP through both hands.

3.3.4 Two parameters to evaluate the bilateral transfer of force perception

The magnitude of force and direction of force perception/generation were used the parameters of two experiments.

Bilateral transfer of force perception and a magnitude of force

Table 3.1 shows the experimental conditions when the experiment parameter is the magnitude of force. In this experiment 1, we set the TF from 5N to 25N with five steps. The direction of bilateral transfer, from left to the right and vice versa, and non-simultaneous and simultaneous conditions can be realized in the experiments. Thus, there are 20 experimental conditions. 15 trials were performed in each condition. Each condition of Table 3.1 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

Target force[N]	Non-simultaneous		Simultaneous	
	Left	Right	Left	Right
5,10, 15, 20, 25	Perception	Regeneration	Perception	Regeneration
	Regeneration	Perception	Regeneration	Perception

Table 3.1 Experiment conditions for the magnitude of force

conditions for each subject and had each subject take a 10 minute break between conditions in the experiment.

Bilateral transfer of force perception and direction of force

In the case of the direction of force, experiment 2, the experimental conditions are as shown in the Table 3.2. 'F' and 'B' means the direction of force; forward and backward, respectively, and the order is from left to right hand. For examples, 'B-F' means backward for the left hand and forward for the right hand. Even if the direction of force is backward, we set the direction of the TP and CB is displayed to move upward as well as experiment 1. Therefore, to avoid mistakes, before starting the experiment, the subject is instructed direction of force. Target force is 15N in all conditions. The direction of bilateral transfer and non-simultaneous/

Direction of Force (Left-Right)	Non-simultaneous		Simultaneous	
	Left	Right	Left	Right
F-F, B-F, F-B	Perception	Regeneration	Perception	Regeneration
	Regeneration	Perception	Regeneration	Perception

Table 3.2 Experimental conditions for the direction of force

simultaneous conditions can be realized in the experiments. The subject takes a 10 minute break between conditions and performs the experiment which randomly determined order for each subject.

3.4 Experimental Results

3.4.1 Data measurement and analysis

The task performance was measured by how well the subject regenerated the TF that was perceived with respect to their contra-lateral hand in the perception mode. According to the research report, it takes about 0.18~0.2 sec. so that human reacts with respect to the visual stimulus (Nishida et al., 1978). Additionally, in order to generate a stable force, the subject needs a time to reduce the fluctuation. In this study, thus, we evaluate latter half of times (1.5 sec) when the TP stops at the TF for 3 seconds as shown in the Figure 3.5.
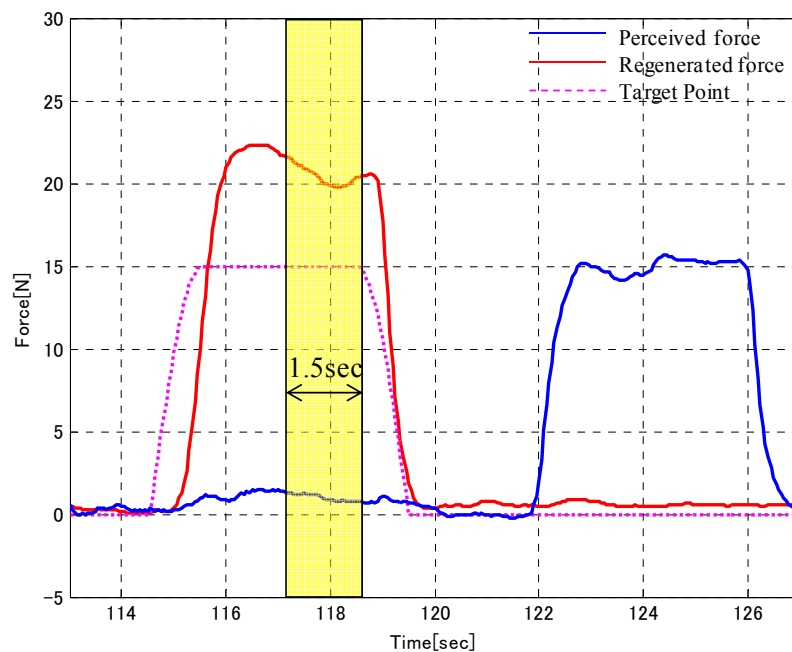
Figure 3.5 Illustration of the target range for evaluation

In this study, we use two evaluation variables; E is mean values of the absolute value of error between the TP and generated force by the subject, and J indicates the evaluation function of the force perception and regeneration task which the E divided by the TP: dimensionless number as described in (3.1). Thus, J means the error ratio with respect to the TF and it allows to compare the regenerating performance among different TPs. When the J is nearer to the 0, the better regenerating performance is revealed.

$$J = \frac{1}{S}\sum_{i=1}^{S}\left(\frac{1}{N}\sum_{j=1}^{N}\frac{|T - M(i,j)|}{T}\right), \quad S = 10, N = 30 \qquad (3.1)$$

Here, T is the TF, and i and j mean trial and sampling number; thus, M(i, j) is the generated force by the subject.

3.4.2 Result of experiment 1

Figure 3.6 shows results of one subject in both the non-simultaneous and simultaneous tasks of time series with the left perception and right regeneration

(a) Non-simultaneous task   (b) Simultaneous task
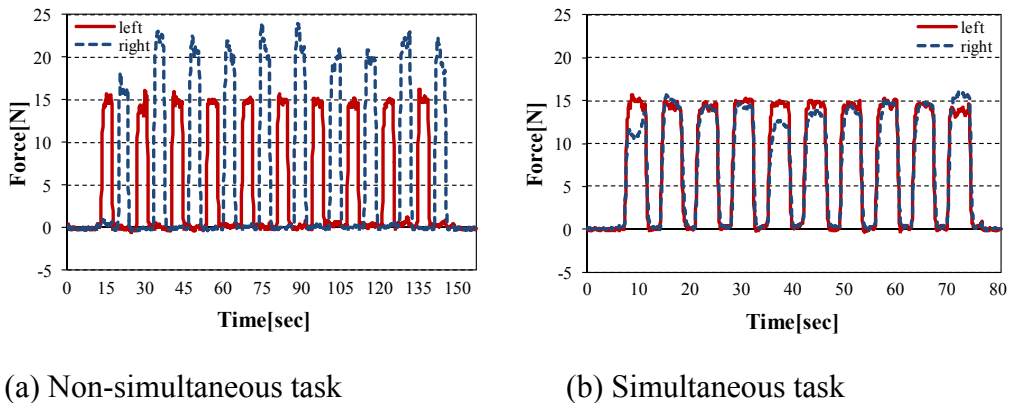
Figure 3.6 Time series of generated force for experiment 1

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mode when the TF is set on the 15N as an example. The results indicated that the subject could accurately regenerate the TF in the simultaneous task.

Figure 3.7 and Figure 3.8 show the experimental results of three subjects with respect to the evaluation variable E in the non-simultaneous and simultaneous task, respectively.

(a)Left perception-right regeneration

(b)Right perception-left regeneration

Figure 3.7 Evaluation variable E of three subjects in the non-simultaneous task

(a)Left perception-right regeneration

(b)Right perception-left regeneration
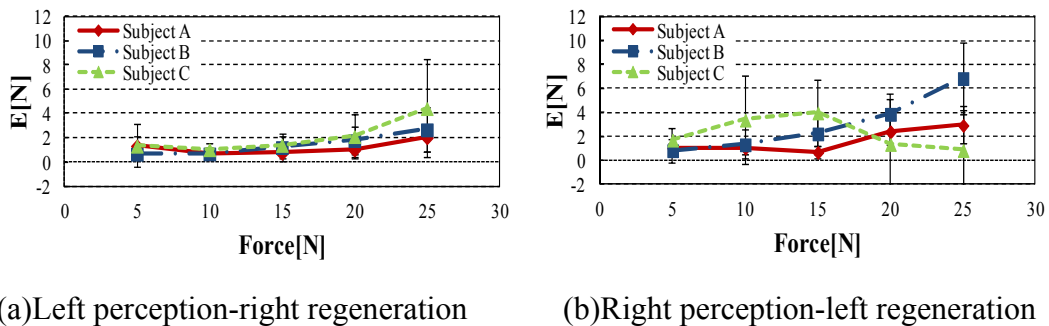
Figure 3.8 Evaluation variable E of three subjects in the simultaneous task

According to the Figure 3.7 and Figure 3.8, a similar trend has been demonstrated that the evaluation variable E was not varied by the TF, in both non-simultaneous (Figure 3.7) and simultaneous (Figure 3.8) conditions. When the TF was 5[N], however, the evaluation variable E and its deviation were larger than another TF. Because of the small magnitude of the TF, it may be difficult to

perceive in precisely. And also, when the TF was 25[N], the evaluation function J of (3.1) and its standard deviation were larger than another TF. It is generally accepted that muscle fiber types can be divided into two main types: slow twitch (Type I) muscle fibers and fast twitch (Type II) muscle fibers (Pocock and Richards, 2009). The Type I muscles are more efficient for continuous and extended muscle contractions over a long time. Type II muscle fibers are much better at generating short bursts of strength or speed than slow muscles. However, Type II muscle fibers generally difficult to produce the same amount of force in precisely. Based on these mechanisms for recruitment of muscle fibers, these results indicated that it was difficult to generate the larger muscle force in precisely.

Figure 3.9 and Figure 3.10 show the experimental results of three subjects with respect to the evaluation variable J in the non-simultaneous and simultaneous task, respectively.
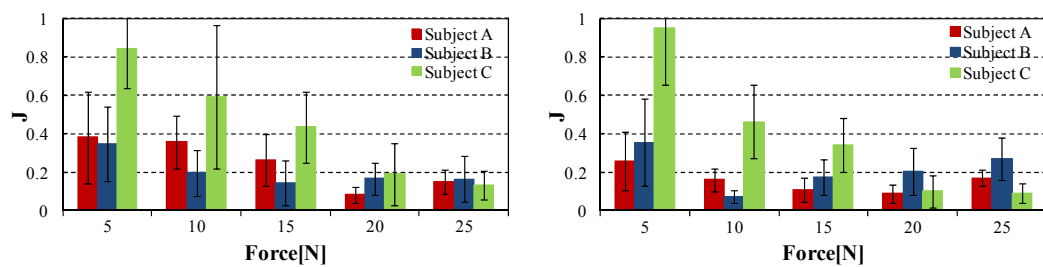
(a)Left perception-right regeneration   (b)Right perception-left regeneration

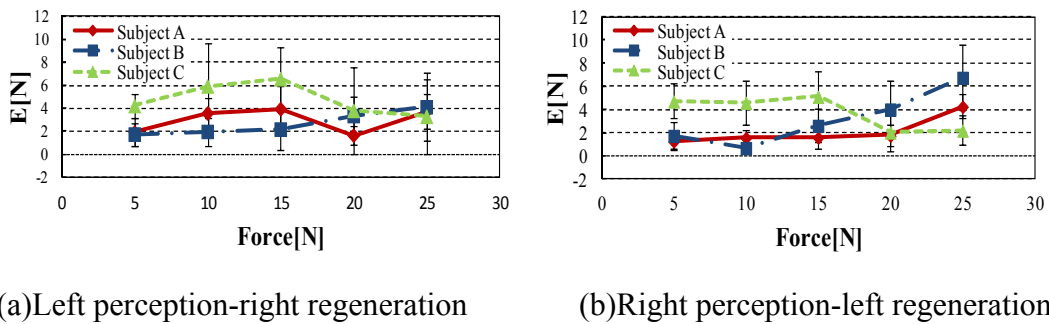Figure 3.9 Evaluation variable J of three subjects in the non-simultaneous task
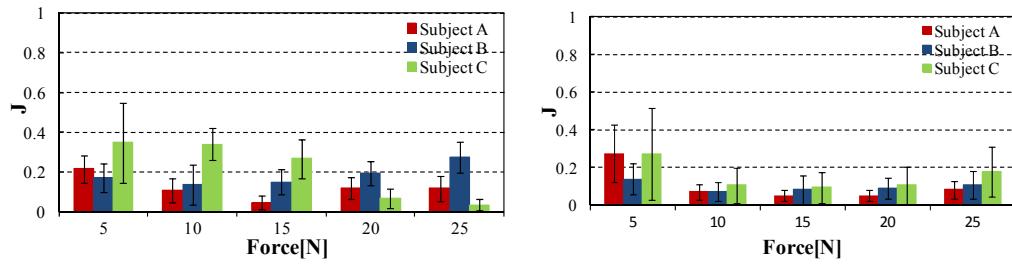
(a)Left perception-right regeneration   (b)Right perception-left replication

Figure 3.10 Evaluation variable J of three subjects in the simultaneous task

To verify the effect of simultaneity on the performance of force regeneration, a paired-sample t-test was applied to the E and J in both the left perception-right regeneration and right perception-left regeneration modes in order to detect the significant difference between the non-simultaneous and the simultaneous tasks. In the case of the E in the subject B, there was no significant difference between the non-simultaneous and the simultaneous tasks (10N: p=0.129, 15N: p= 0.568, 20N: p=0.808, 25N: p=0.946). On the contrary, for the subject A and C, the evaluation variable E and J indicated the significant difference between the non-simultaneous and simultaneous conditions. In the simultaneous task, since the subjects performed the force perception and regeneration modes at the same time, the regenerating performance could be better than the non-simultaneous task which should exists a time delay between force perception and regeneration modes. Additionally, according to the smaller deviations for the J, in the simultaneous task, it was clear that the subject could perform stable and accurate force regeneration. Based on these results, we indicate that the bilateral transfer of force perception is the function of the simultaneity and the magnitude of force.

As shown in the Figure 3.10 (a), the left perception-right regeneration mode in the simultaneous task indicated that the E and J, and theirs deviation were smaller than any other modes in the non-simultaneous and simultaneous modes. And all subjects demonstrated a similar trend. This means that bilateral transfer of force perception for the right handed subjects were more accurately occurred in the direction from the left (non-dominant) to the right hand (dominant). This result is consistent with several previous reports of the bilateral transfer of spatial and temporal perception which investigated the direction of transfer (Inui, 2005; Kumar and Mandal, 2005). They indicated that right-handed subjects demonstrated better results when the direction of transfer is from left(non-dominant) to the right(dominant) hand rather than opposite. To compare the difference between the unimanual which perform the regeneration after the perception with one side of the hand (i.e., non-simultaneous task, but not bilateral transfer task) and the bimanual tasks, the subject A conducts
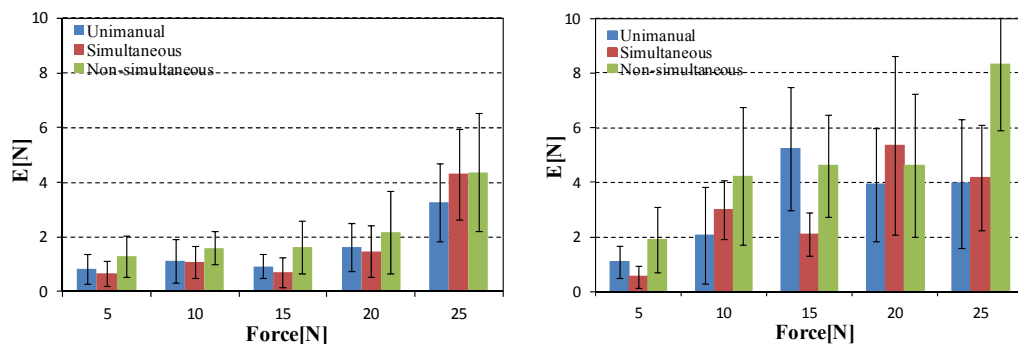
(a)Left perception-right regeneration   (b)Right perception-left replication

Figure 3.11 Evaluation variable E in the three types of task; unimanual, simultaneous, and non-simultaneous. In the case of the unimanual task, (a) is left perception-left regeneration mode and (b) is right perception-right regeneration mode.

the additional experiment, i.e., the perception-regeneration unimanul task. The figure 3.11 shows the comparison result of three types of tasks. Even though the force regeneration performance of unimanual task was better than the non-simultaneous task, it was almost same or slightly worse for the comparison with simultaneous task. These results reveal the effect of time delay and bilateral transfer which the subject performed the regeneration with ipsilateral or contra-lateral hand in the tasks.

3.4.3 Result of experiment 2

In this passage, we will discuss about the result of experiment 2 which investigated the relationship between bilateral transfer of force perception and direction of force. Figure 3.12 shows results of one subject both the non-simultaneous and simultaneous task in time series with the left perception and right regeneration mode when 'F-B' condition. The result showed that the subject could perform the accurate force regeneration in the simultaneous task.
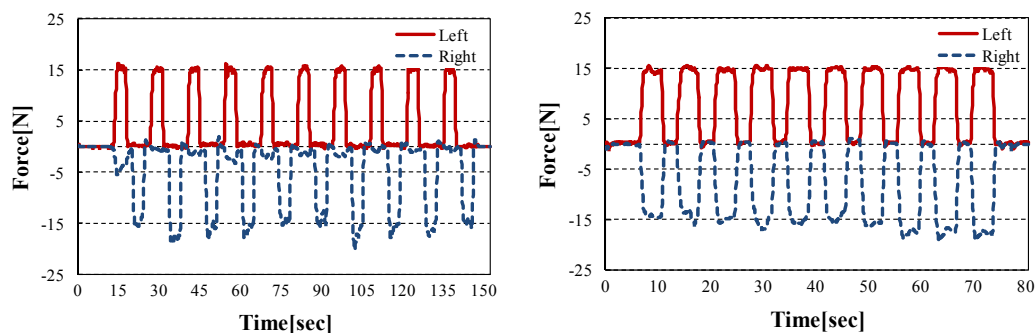
(a) Non-simultaneous task　　　　　　　(b) Simultaneous task

Figure 3.12 Time series of generated force for experiment 2
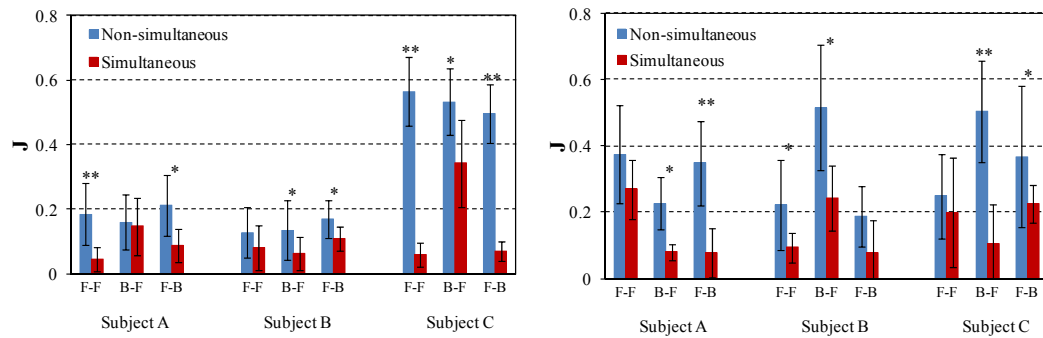
(a)Left perception-right regeneration (b)Right perception-left replication

Figure 3.13 Evaluation value J of the all subjects for all conditions of the direction of force in the non-simultaneous and simultaneous task (*:$p<0.05$, **:$p<0.01$).

To investigate the effect of direction of force on the bilateral transfer of force perception, the 'B-F' and 'F-B' conditions were compared with 'F-F' condition by the evaluation value J as shown in the Figure 3.11. In the case of simultaneous conditions, the comparison results between 'B-F' and 'F-F' conditions revealed that the subject B and C for left perception-right regeneration mode showed a larger difference as 0.29 and 0.25, respectively. In addition, the subject C for the right perception-left regeneration mode showed the difference between 'B-F' and 'F-F' conditions as 0.28. It may be the effect of handedness; which non-dominant(left) hand revealed the lack of the perception and regeneration compared with dominant(right) hand. Except these three cases, a similar trend has been demonstrated that the evaluation variable J was not varied by the direction of force, in both left perception-right regeneration mode and right perception-left regeneration mode. Overall, these results indicated that the direction of force did not affect the bilateral transfer. In other words, the bilateral transfer of force

perception actively occurs regardless of the direction of force. It means that human can program the command for the regeneration of similar force which perceived with contra-lateral hand by a simulation occurred in the brain (Hesslow, 2002).

Additionally, a paired-sample t-test was applied to the evaluation variable J in order to verify the effect of simultaneity on the bilateral transfer of force perception as shown in the Figure 3.13. Even though the directions of force were varied by the each condition, the performance of force regeneration is better in simultaneous conditions for both the perception-regeneration modes.

3.5 Conclusion and Discussion

In the robot-aided rehabilitation systems, a patient and robot systems interact with each other by physical contact. Therefore, human sensory systems to perceive a movement and resistive or assistive forces provided by robot-aided rehabilitation systems should be much more considered. In this chapter, we focused on the bilateral transfer of force perception, and the magnitude of force and the direction of force were used the parameters in the experiment 1 and 2, respectively. The result of experiment 1 indicated that the bilateral transfer of force perception is the function of the simultaneity and the magnitude of force. The better regenerating performance was obtained when the subject performed the force perception and regeneration task at the same time. Therefore, we assume that simultaneous bilateral movement training will be induced more effective rehabilitation outcomes.

The bilateral transfer of force perception actively occurs regardless of the direction of force was identified by the experiment 2. Hesslow (2002) suggested the simulation theory based on the three assumptions about brain function: behavior, perception and associative mechanisms of behavior and perception. First, the behavior can be simulated by activating motor structures of the brain which is similar to the same activation during normal actions without any overt movement. And perception can be simulated by internal activation of sensory cortex as same as actually perceiving external stimuli without actual perception of it. Finally,

there exist associative mechanisms that enable both behavioral and perceptual activity to elicit other perceptual activity in the sensory areas of the brain. Based on this simulation theory, even though direction of force was different between the perception and the regeneration modes, the subject could regenerate the similar magnitude of forces with respect to perceived target forces in the contra-lateral hand as the result of experiment 2. Therefore, various directions can be used in the planning the rehabilitation training games which provide the force perception and regeneration bimanual tasks to increase the patient motivation.

Recently, bilateral movement training is considered as a current prominent rehabilitation protocol for upper extremities. Based on the overall results of this chapter, we can provide the insight into for planning more effective bilateral movement training. Specifically, the result of left perception-right reproduction mode which transfer is actively occurred can be the indicator of rehabilitation to accomplish the trainings.

Chapter 4

Planning of Bilateral Movement Training based on the Bilateral Transfer of Proprioception and Force Perception by using Virtual Impairment

4.1 Introduction

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. One of the most distinct benefits with robot-aided rehabilitation systems is, for the effective rehabilitation, freely creating various bilateral movement trainings which induce much more interaction between upper

extremities. The bilateral transfer of sensory information 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 main goal of this dissertation, based on the bilateral transfer of sensory information, is to find the exact conditions that would cause much more interactions between upper extremities for upper extremities rehabilitation. Thus, in the previous two chapters, we have discussed the bilateral transfer in sensory system, especially proprioception and force perception, which were the most important factors for robot-aided rehabilitation system. As shown in the Figure 4.1, in this chapter, using the results of the previous two chapter's studies, we focus on the planning of bilateral movement training which induce the much more interaction between upper extremities. The active/passive conditions and loaded/non-loaded conditions were selected based on the chapter 2 and the chapter 3, respectively.
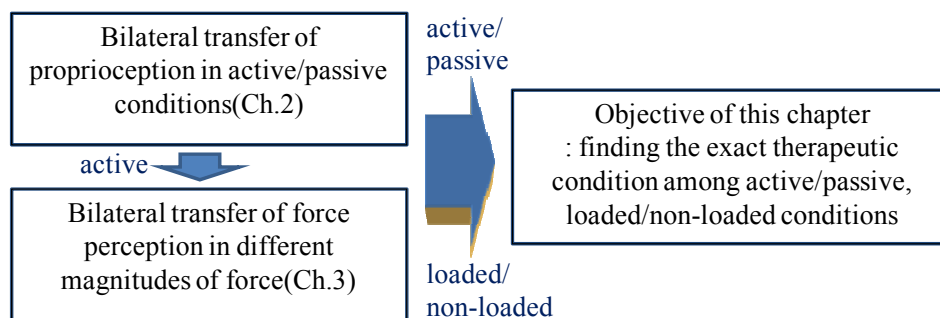
Figure 4.1 The objective of this chapter, in which relate to the chapter 2 and chapter 3.

4.2 Background and Motivation

Since the studies of the interlimb coordination and bilateral transfer in healthy subjects have great merit for understanding disordered behavior and for planning rehabilitation training of protocol, these have been potentially important topics in post-stroke rehabilitation (Swinnen and Carson, 2002). The analysis of relative phase angle and movement frequency between limbs was used to evaluate the characteristic of interlimb coordination (Swinnen, 2002). For example, Malabet et al. (2010) investigated the bimanual symmetric motions based on a physical path tracking task with omni force feedback devices in three reference frames: joint space symmetry(JSS) where the motions are mirrored and the joints on each limb follow the same angles, visual symmetry(VS) where the hands move in the same Cartesian directions, and point mirror symmetry(PMS) where the hands rotate around an arbitrary point in space. The majority of investigations of bilateral transfer are mainly about the transfer direction, the effect of handedness and the bilateral transfer of learning: from right to left side of the body or vice versa, laterality and sensory or motor information (Buchan, 2004; Sainburg, 2002).

4.2.1 The bilateral movement training in the robot-aided rehabilitation system

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 (Lum et al., 2006; Gupta et al., 2008; Ito et al, 2011). 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 for effective rehabilitation therapy. In the robot-aided rehabilitation systems which support the bilateral movement trainings, thus, it is important to find the exact conditions that would cause much more interaction between upper extremities in order to plan effective bilateral movement training.

4.2.2 Objective of this chapter

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 the previous two chapters, 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, which were the most important two factors for robot-aided

rehabilitation system. The recovery and reorganization of lost motor function can be obtained with the accurate sensory feedback. The proprioception plays an important role for goal-directed movements which consists of the most common physical therapy. According to the chapter 2, 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 the result, to verify the effect of voluntary motor function, active and passive conditions were used in this chapter.

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, bilateral transfer of force perception is also important factor which should be discovered. The result of the chapter 3 indicated that the bilateral transfer of force perception was the function of the magnitude 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. Figure 4.2 summarizes the subjects group which divided by the experimental results of the chapter 2 and chapter 3. Orange color means the four experimental conditions which used in this chapter. Firstly, the result of chapter 2 applied to passive groups and active loaded and non-loaded groups: green in the Figure 4.2. Blue means that the active non-loaded and loaded groups were divided by the result of chapter 3. Lastly, comparison

	Non-loaded condition	Loaded condition	
Passive Group(PG)	Active Non-loaded Group(ANLG)	Active Loaded Group(ALG)	Control Group(CG)
Passive condition	Active conditions		unilateral condition
bilateral conditions			

Figure 4.2 four experimental conditions divided by the result of chapter 2 and chapter 3.

between bilateral and unilateral conditions was verified by the control group.

The objective of this chapter is the investigation of the effect of different conditions which are imposed on the unimpaired upper extremity for planning more appropriate bilateral movement training based on the robot-aided rehabilitation systems. In this chapter, based on the previous two chapters' results, 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.

4.3 Methodology

4.3.1 Force fields 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 (Reinkensmeyer et al., 2004). In the typical study (Shadmehr & Mussa-Ivalidi, 1994), 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. (2000) 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.

4.3.2 Virtual impairment

Emken et al. (2007) 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 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. (2000) as mentioned in the previous phrase 4.3.1. 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 based on the neural cross talk(review in Chapter 1.3.3), the persistence of motor adaptation was varied by the conditions of one upper extremity in the bilateral movement. Based on this hypothesis, we investigate 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 (Lange et al., 2006; Schulze et al., 2002), right-handed subjects demonstrated better results when the direction of transfer is from left(non-dominant) to the right(dominant) hand rather than opposite (Inui, 2005; Kumar and Mandal, 2005; Park et al., 2011). 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.

4.3.3 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 (Oldfield, 1971). 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 a 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 their 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).

4.3.4 Experimental apparatus

In this study, we used same experimental apparatus introduced in the chapter 2 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. During the experiments, the subject is asked to concentrate on the monitor. The motions of manipulator are restricted on the horizontal plane
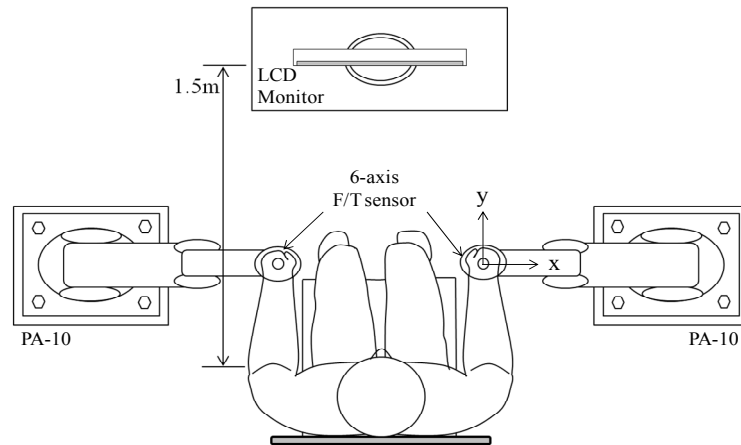
Figure 4.3 Top view of experimental setup

(xy plane in Figure 4.3). 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 (4.1), i.e. impedance control. This equation is well-established in the field of robotics and human robot interaction (Cheah et al, 1998).

$$F = M\ddot{z} + D\dot{z} + Kz \qquad (4.1)$$

The position x and y were calculated based on the (4.1), 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 (4.1) for calculating the x position, and y position was obtained by substituting y-axis force into (4.1). 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 backdriveability 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 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.

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($[v_x, v_y]^T$).

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} 0 & -P \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \end{bmatrix}$$
(4. 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 4.3. Thus, the calculating the x position with the (4.1) 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. (2000).

4.3.5 Reaching Task

During entire experimental sessions, the subjects were asked to make a reaching movement from the start point to the end point displayed on a LCD monitor within two seconds. Figure 4.4 shows an example of experimental display when the target point locates at the end point. A small white circle presented the current hand positions of the subject, and the start and end points were displayed as blue circles as shown in the Figure 4.4. These start and end point 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 red 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
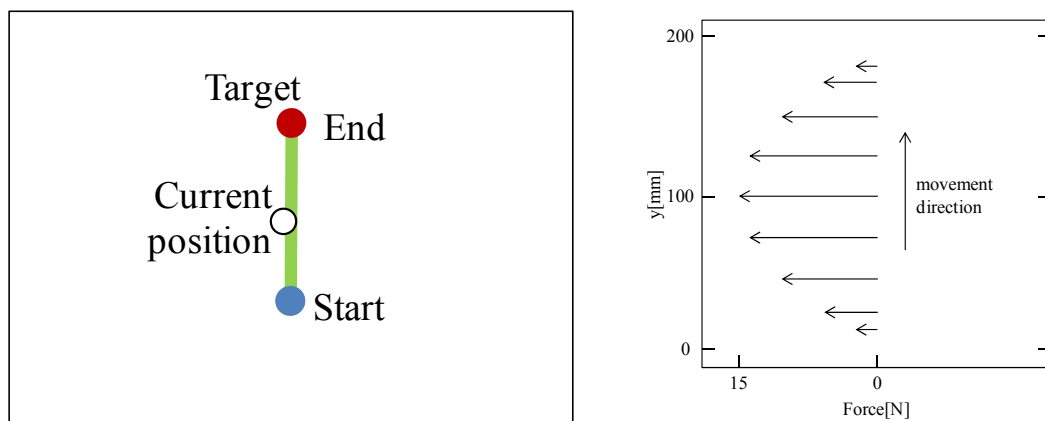
Figure 4.4 Example of experimental display when the target point located at the end point, and perpendicular forces with a bell-shaped velocity profile.

end point. Thus, the subject was asked to make a movement to reach the end point when the target point was moved from the start point to the end point. A green 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 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.

4.3.6 Experimental conditions and procedures

The subject sat on a chair that was located in midway between the two manipulators and was asked to hold onto the right knobs with their right hand during the force field adaptation phase for all subjects. In the channel phases, depending on the experimental groups, the subjects were asked to grip with their left hand as well for bilateral movement. Table 4.1 shows the experimental conditions which were performed by the subject of each group. In the passive condition, the robot guides 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 those of the controlled position in the monitor.

The experiments consisted of three phase: pre-channel phase, force field adaptation phase and post-channel phase. The pre- and post-channel phase consisted of 50 channel movements performed in the mechanical guide bounding

TABLE 4.1

EXPERIMENTAL CONDITIONS

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

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.

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 his/her both hand for bilateral group while the CG perform 50 movement channel field 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.

4.3.7 Measurement and analysis

To evaluate the subject performance, we used measures of kinematic and dynamic behavior on simple goal-directed reaching task which is referred to research of Scheidt et al. (2000). 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 which the forces were unexpectedly removed; catch trials have been used to assess adaptation by characterizing its aftereffect. However, the recent evidence suggests that catch trials may themselves influence and degrade adaptation (Shadmehr and Brashers-Krug 1997; Thoroughman and Shadmehr 1997). We did not apply the catch trials to prohibit disturbing the adaptation process. To verify the effect of conditions which 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 trial number of the reaching movement for the recovery from the adaptation (i.e., the number of disadaptation) was measured as the persistence of motor adaptation in the post-channel phases. Therefore, the number of disadaptation has the units [trials] since the sampling interval for measures of magnitude of the dynamic

performance was 1 trial. When the magnitude of dynamic performance was smaller than 0.5N during the reaching movement in the post channel phase, the number of disadaptation was determined. For example, if the magnitude of dynamic performance of the subject is smaller than 0.5N in the fifteenth trials, the number of disadaptation is 15. Based on the bilateral transfer aspect, the number of disadaptation is varied by the conditions of the left upper extremity. The smaller trial number of the disadaptation can be induced by actively causing bilateral transfer. Thus, the result with smaller trial number of the disadaptation means more effective condition for effective bilateral movement training. By comparing the number of disadaptation measured in the each condition, we found the exact condition for planning of effective bilateral movement training.

4.4 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 Oldfield (1971), ranged from 86.8 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.

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 4.2 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.

TABLE 4.2

THE TRIAL NUMBER OF DISADAPTATION

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

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.

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4.4.1 Verification of persistence of motor adaptation

According to Scheidt et al. (2000), 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 phrase, we also verified the investigation result of Scheidt et al. (2000) about persistence of motor adaptation. Figure 4.5 (a) and (b) shows the hand force profiles perpendicular to the direction of movement 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 4.5 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. Based on this result, we applied the characteristic of the persistence of motor adaptation to our evaluation method.
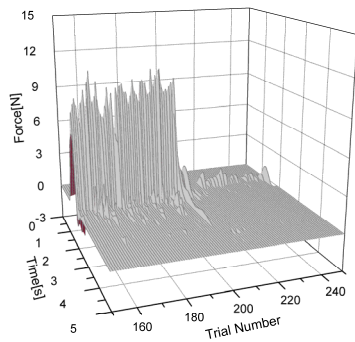
(a)with kinematic errors   (b)without kinematic errors
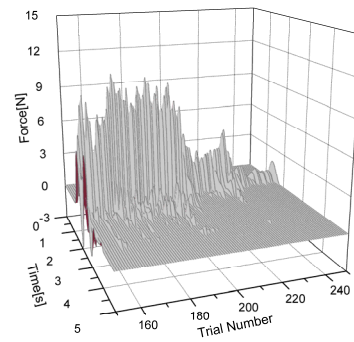
Figure 4.5 Hand force profiles perpendicular to the direction of movement on the trials immediately preceding and immediately following the transition from perpendicular field(trials 151-200) movements to channel field(201-250) movements.

4.4.2 Comparison between the active and passive

Figure 4.6 shows the hand force profiles of one subject of four groups. Based on the results shown in Table 4.2, the comparison between active and passive conditions which were imposed on the left upper extremity indicateed 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 4.7 shows the results of Mann-whitney test for the number of disadaptation with respect to the four conditions group. Note that the p-values of the comparison between PG and ANLG is 0.07, thus there was marginally 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.

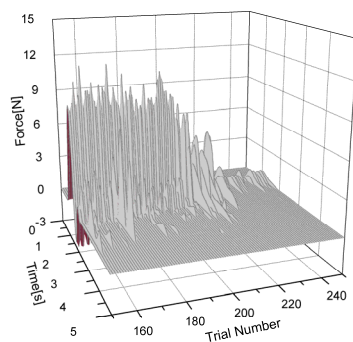(a)Passive Group
(b)Active Non-Loaded Group
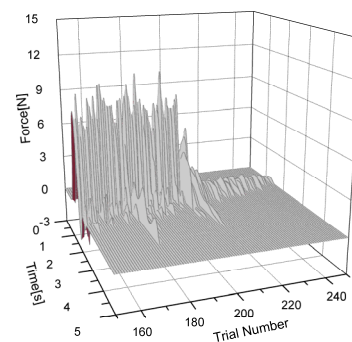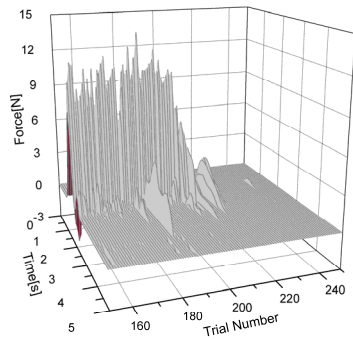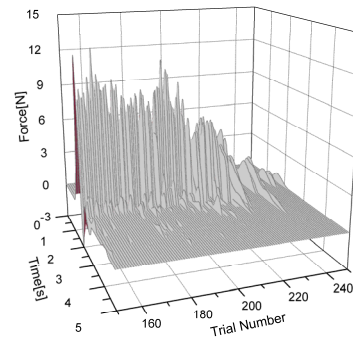
(c)Active Loaded Group　　　　　　　　(d)Control Group

Figure 4.6 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.

4.4.3 Comparison between the bilateral and unimanual

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 4.2, 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 4.6. According to the Figure 4.7, 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.
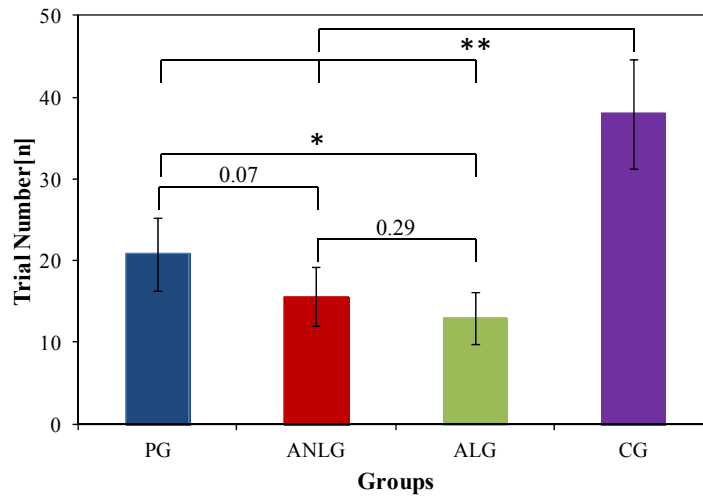
Figure 4.7 Mean of the five subjects' trial number for the each group. The values of the Mann-whitney test are shown in the figures, where * means $p<0.05$ and ** means $p<0.01$ or the p-value is shown.

4.4.4 Comparison between the loaded and non-loaded

To verify the effect of resistive load on the movement, we compared the result of the ANLG and ALG. As shown in the Figure 4.3 (b) and (c), 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 4.2 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 4.7, there was no significant different between active non-loaded and active loaded groups ($p<0.29$).

4.5 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 chapter, 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 chapter 2 which bilateral transfer of propriception was actively occurred with the voluntary movement. Therefore, based on the result of chapter 2

and this result, active bilateral movement training would cause much more interactions between upper extremities is better for upper extremities rehabilitation.

In this chapter, we 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 chapter 3, 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.

4.6 Conclusion

In this chapter, using the results of the previous two chapter's studies, we focused on the finding the exact 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 overall results of this chapter are summarized in the Figure 4.8.
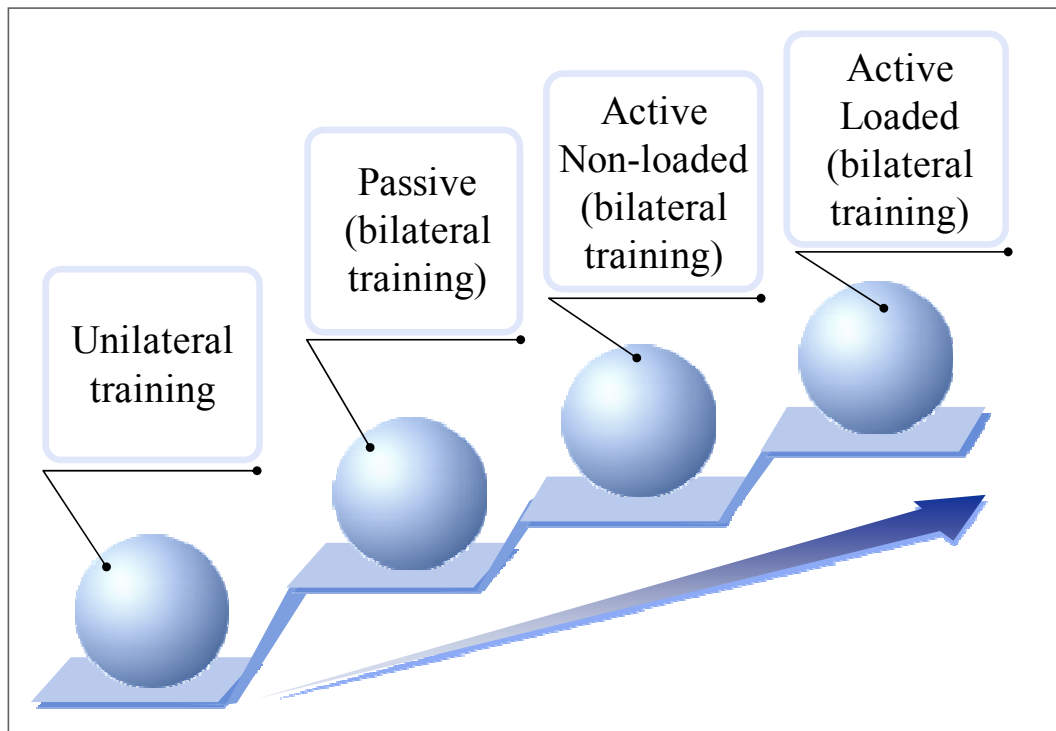
Figure 4.8 Summary of comparison result to find therapeutic conditions for effective rehabilitation based on the result of this chapter.

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 as shown in the Figure 4.8.

Chapter 5
Summary of Contributions and Future Work

5.1 Summary of Contributions

This dissertation discusses the bilateral transfer of human sensory system to plan more effective bilateral movement training for robot-aided upper extremity rehabilitation system. The major contributions of this dissertation described from the chapter 2 to the chapter 4 are summarized in the following sections.

5.1.1 Bilateral transfer of proprioception

We investigated the bilateral transfer of proprioception based on the property of muscle spindle. The proprioception is generally believed to control the

awareness of joint angle, motion and force (Farrer et al., 2003) and to play an important functional role in the control of goal-directed movements which consists of the most common physical therapy (Hasam et al., 1992; Dannenbaum et al., 1993; McNair et al, 1996). The muscle spindles, the primary source of proprioception, are subject to central fusimotor control (Proske et al., 2000), the sensitivity of muscle spindle is varied by muscle activity patterns and commands in passive and active movements (Laufer et al., 2001). Thus, 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 based on the active and passive guidance-reproduction in bimanual tasks were used in this study. To verify the effect of simultaneity on the reproducing performance, non-simultaneous and simultaneous tasks were used in this study. In order to evaluate the proprioceptive signal acquired from the guidance based reaching motion, the subjects were asked to reproduce the mirror-symmetrical motion with respect to the motion of the contra-lateral upper limb at the same time or after guidance in simultaneous and non-simultaneous tasks. The experimental results indicate that more accurate reproducing performance is obtained when the proprioceptive sensory feedback is acquired from the active guidance condition. The result of simultaneous task has been demonstrated better reproducing performance than the result of non-simultaneous task. 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, the direction of bilateral transfer of proprioceptive feedback was better from the left(nondominant) to the right(dominant) rather than the opposite; in terms of the direction of bilateral transfer, this result was consistent with the previous research result, even though the main goal of each study was different, right-handed subjects demonstrated better results when the direction of transfer was from left(non-dominant) to the right(dominant) hand rather than opposite(Inui 2005; Kumar and Mandal, 2005).

5.1.2 Bilateral transfer of force perception

During rehabilitation training with robot-aided rehabilitation systems, robots commonly resist the movements of upper extremity or compensate the gravity force of the upper extremity itself by physical contact. Therefore, to plan more effective bilateral movement training adaptive to robot-aided rehabilitation, the characteristic of human sensory systems perceiving resistive or assistive forces provided by robotic devices should be verified. Therefore, we investigated the bilateral transfer of force perception. The force perception-regeneration bimanual tasks in isometric condition without the movement of upper extremities were used in order to focus on only force perception; in the perception-regeneration bimanual task, the subjects were asked to push or pull the joysticks which forces applied to forward/backward direction to the force sensor. In order to evaluate the bilateral transfer of force perception, the subjects were asked to regenerate the same force which perceived on the contra-lateral upper extremity. There were two

conditions; the non-simultaneous task in which the subjects were asked to regenerate the same force as perceived one in perception mode after force perception, and the perception and regeneration modes were performed at the same time in the simultaneous task. The magnitude of force and the direction of force perception/generation were used the experimental conditions. The experimental results indicate that the bilateral transfer of force perception is the function of the simultaneity and the magnitude of force. Additionally, the bilateral transfer of force perception actively occurred regardless of the direction of force.

5.1.3 Planning of bilateral movement training

For the effective rehabilitation, a robot-aided rehabilitation system is able to create various bilateral movement trainings freely. The main goal of this dissertation, based on the bilateral transfer of sensory information, is to find the exact conditions that would cause much more interaction between upper extremities for effective upper extremities rehabilitation since the interaction induces the neural plasticity for the rehabilitation. Thus, we have investigated the bilateral transfer of proprioception and force perception which are the most important factors to be considered for robot-aided rehabilitation system. Using the research result of bilateral transfer, we investigated the effect of conditions which were imposed on the one upper extremity to arise the more interaction between upper extremities for effective bilateral movement trainings. Active/passive, loaded/non-loaded, and unimanual/bimanual movements were used as the

experimental 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 subjects conducted the aftereffect test which consist of a bimanual movement task while the control subjects performed a unimanul movement task. The trial number of reaching movements for recovery from motor adaptation in the right upper extremity was used as the evaluation variable. We purposed that, based on the bilateral transfer, the trial number of disadaptation was varied by the conditions of left upper extremity in bimanual movement. When upper extremities actively interact with each other, the trial number of disadaptation will be reduced. Thus the condition promoting the much more interaction induces the faster recovery from the motor adaptation and is adaptive to effective bilateral movement training. The result indicates that the trial number of disadaptation is smaller in the active condition than in the passive. The comparison results between non-loaded and loaded conditions show that the trial number of disadaptation of the non-loaded group is larger than active loaded group. Contrary to expectations, there was no significant difference between two groups within statistical test. Since we set the resistive force for active loaded group with same magnitude of force, it was possible that obvious difference between the loaded and non-loaded conditions was not disclosed.

5.2 Future Work

Brief directions and topics for future work in the research areas associated with this thesis are as follows

5.2.1 Brain activity during bilateral transfer of proprioception and force perception

We discussed the bilateral transfer of proprioception and force perception based on the use of robot manipulator and sensor systems. Therefore, fMRI based study is need to investigate the brain activity to support our research results when the subject performs the tasks which used in these studies. However, for the evaluation, a robot manipulator and sensors systems can not be used with fMRI system together because fMRI systems release strong magnetic field. Therefore, at first, we need to construct the suitable experimental apparatus which substitute the robot manipulator and sensor systems for use in fMRI by the use of non-magnetic materials. In addition to the investigation of propriocpetion, since human sensory-motor system includes both spatial and temporal characteristics, 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.

It is proposed that rehabilitation therapies promoting active use of sensory feedback such as visual or auditory information may be definitely effective since a

key process in recovery of motor function after stroke is the sensorimotor integration in the brain. We use only the visual feedback information for the simple tracking task. Therefore, further experimental investigations are needed to verify relations of auditory feedback to the bilateral transfer aspects and combinations between the visual and auditory modalities.

5.2.2 Computational model of bilateral transfer

Recently, the sensory and motor system has been the subject to quantitative and computational characterization. Thus, many researcher are trying to built computational model which identifies the sensory feedback and motor control processes. According to the reviews of Shadmehr and Krakauer (2008), this computational approach has clear benefit to support understanding sensory and motor characteristic of both patients and healthy people. They suggested that the lesion approach of patients and theoretical motor control could mutually inform each other. Specifically, one may identify distinct motor control processes from computational models and map them onto specific deficits in patients. Many research based on the experimental and theoretical work has been conducted with visually guided reaching movement. However, the research of computational models for bilateral transfer aspect is not sufficient even though many experimental results reported the characteristics of bilateral transfer. Thus, we plan to concentrate on the computational model of bilateral transfer with sensory and motor systems.

5.2.3 Implementations for rehabilitation therapy

In chapter 4, we investigated the conditions which imposed on the one upper extremity to induce the more interaction between two upper extremities using the investigation result of chapter 2 and 4. The results indicated that bilateral movement training with active loaded condition induced much more interaction between upper extremities. Since studies with healthy subjects may also suggest hypotheses as to the type of bilateral movement training, the discussion with physical therapist is necessary for implementations of our results to real physical rehabilitation training with robot systems.

The robotic system can be very harmful in the case of an emergency such as during a malfunction. Especially, when human contact with the robotic device or machine to realize a robot-aided rehabilitation system, the safety and stability of system must be always guaranteed for both patient and therapist. During all experiments conducted for this dissertation, we set several surveillance routines which were implemented in the software such as force/speed monitoring in the present time and a robot self-collision detection algorithm for the safety. In addition to these basic software safety features, redundant hardware safety features should be also considered to construct the robot-aided rehabilitation systems such as mechanical end stops to guarantee that any joint can not exceed the anatomical range of motion of the limbs.

Motivation to exercise for longer periods of time with intentional movement is believed to determine the rehabilitation outcomes. Recently, augmented virtual

reality systems composed of haptic and visual reality systems have received a great deal of attention as a method to encourage the patients' motivation. In our experiments, the tasks consisted of simple reaching movement; it was not interesting. Thus we are planning to develop robot-aided rehabilitation systems consist of the virtual reality techniques and a mazelike computer game.

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Curriculum Vitae

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2007-2009: Degree: MS in Mechanical Engineering (Title: The Development of a
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1999-2007: Degree: Bachelor in Science, Mechanical Engineer
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Projects: Task based robot design for Robot Contest (ROBOCON).
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PUBLICATIONS

1. **<u>Keunyoung Park</u>**, Youngwoo Kim, Chikara Nagai, and Goro Obinata, "Bilateral Transfer in Active and Passive Guidance-reproduction of Upper Limbs Motion: Effect of Proprioception and Handedness", Journal of Biomechanical Science and Engineering, accepted (Dec. 8, 2011).

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PRESENTATION ON INTERNATIONAL CONFERENCES

1. **<u>Keunyoung Park</u>**, Goro Obinata, "The Development of Upper Limbs Rehabilitation Robot System based on the Motor Performance", 6th International Conference on Flow Dynamics, Sendai, Japan, Nov. 4-6, 2009.

2. **<u>Keunyoung Park</u>**, Youngwoo Kim, Goro Obinata, "The Development of Upper Limbs Rehabilitation Robot System Based on the Difference of Motor Performance", IEEE International Symposium on Micro-NanoMechatronics and Human Science2009, Nagoya, Japan, Nov. 8-11, 2009.

3. **<u>Keunyoung Park</u>**, Youngwoo Kim, Goro Obinata, "Investigation of Human Mirror-image for Bilateral Movement Training of Upper Limb Rehabilitation", IEEE International Symposium on Micro-NanoMechatronics and Human Science 2010, Nagoya, Japan, Nov. 7-10, 2010.

4. **<u>Keunyoung Park</u>**, Youngwoo Kim, Goro Obinata, "Bilateral Transfer in Active and Passive Guidance-reproduction Based Bimanual Tasks: Effect of Proprioception and Handedness", 33rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Boston, Massachusetts USA, August 30 - September 3, 2011.

5. **<u>Keunyoung Park</u>**, Youngwoo Kim, Chikara Nagai, Goro Obinata, "Bilateral Transfer in Active and Passive Guidance-reproduction of Arm Reaching Movement: Effect of Proprioception and Handedness", International Symposium on EcoTopia Science 2011(ISETS '11). Nagoya, Japan, Dec. 9-11, 2011.

Acknowledgments

First and foremost, I would like to express my deepest gratitude to my advisor, Professor Goro Obinata, he has given me a chance to meet new research fields; robot-aided rehabilitation systems and human behaviors. He has given me key advice on how to study my own research and detailed advice to improve the way how I develop my argument. All his advice has made me it possible for me to make the first step in my research filed.

Much thanks also to all members of the Obinata Laboratory. In particular, I would like to express a lot of thanks to assistant professor Youngwoo Kim, Chikara Nagai, Satoru Tokuda and Hiroki Takehashi. They have pointed out important questions to be clarified and encouraged me to do my work. And specially thanks to Keisuke Kurita, Kosuke Shimizu, Ryousuke Ito, Yuji Nishikawa, for be always to be willingly a subject in any of my experiments(although Ko…chan was sometimes so tedious..). And I want to mention Shoichiro Kamada who helped me kindly to join the Obinata laboratory. Although I couldn't type all their names, many people helped in various ways for my first step in my field. I would like to thank everyone.

I must mention one of my seniors, Jae-hoon Jung who is working on a Ph. D in Fukuda laboratory at Nagoya University. During last one year, he supported me by giving advices or encouragements to make my first step. I also must mention two friends of mine. Min-Chul Colin Kim and Yong-Gyu Lee's friendships encouraged me so that I could regenerate myself. I gave my thanks to them for being my eternal supporters.

Last, but definitely not least, I thank my family for their unconditional love, and for understanding. And special thanks to my lovely wife, Heejung Yoo, for her love, energy and patience. And hearted affections from my father in law and mother in law have supported me. Words cannot begin to explain my gratitude and love for all my family.

감사의 글

우선, 제가 더 넓은 세상에서 앞으로 나아 갈 수 있도록 격려의 말씀 아끼지 않으시는 경북대학교 기계공학부 시스템 제어 및 자동화 연구실 이상룡 교수님과 지능제어 메카트로닉스 연구실 이준영 교수님께 깊은 감사의 말씀 드립니다.

또한, 학부 3학년부터 지금까지 로봇 설계 및 제작에 필요한 컴퓨터 프로그래밍에서부터 마이크로프로세서 활용 등 다방면으로 많은 가르침 주신 한국 폴리텍 대학 메카트로닉스과 배준영 교수님께 앞으로 더욱 더 많은 기술 전수 부탁 드리며, 깊은 감사의 말씀 드립니다.

경북대학교 기계공학부 로봇 연구 소모임 ROBO에서 함께 활동했던 선배, 동기, 후배 님들에게도 감사의 말씀 전하고 싶습니다. 여러분과 함께한 소모임 활동의 시간들이 박사과정 동안 저를 받쳐주는 원동력이었습니다.

그리고, 경북대학교 기계공학과 시스템 제어 및 자동화 연구실에서 열심히 공부 하고 계신 후배님들에게도 감사의 말씀 전하고 싶습니다. 특히, 소모임에서부터 연구실까지 후배라는 명목으로 어려운 부탁도 마다하지 않고 항상 신경 써서 도와 준 강오현, 류시현 후배님께 고맙다는 말 전하고 싶습니다.

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마지막으로, 이 작은 기적을 보여주신 하느님께 감사의 기도 드립니다.