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Development of Motion Instruction System with Interactive Robot Suit HAL

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***Abstract*— This paper proposes motion instruction system with the interactive robot suit HAL (Hybrid Assistive Limb) for supporting physically challenged persons, enhancing and expanding the human ability. HAL consists of external frames, actuators, various sensors, and a control PC with ethernet device and has not only been developed to assist the motion of wearer's body, but also can be applied to motion instruction between the doctor and the patient in rehabilitation by building the unilateral/bilateral master-slave system with two HALs. In order to realize the motion instruction system, it is required to transfer the information of motion to each other. We performed fundamental experiments for unilateral/bilateral motion instruction between HALs to verify whether the system satisfies the required basic specification, and could confirm the effectiveness of the suggested system.**

I. INTRODUCTION

The motion instruction system is a system that enables a person to make instructed motions when being taught by another person. When a human masters a physical motion, there are several ways to learn it. If a learner imitates a teacher or master as a model, the learner uses his/her own sense of sight. When a teacher explains how to correctly move, the learner uses sense of hearing. In the case of tennis or golf et al., a coach holds the student's hand to give a guidance of the explanation of target motion like 'swing'. The student uses somatic sensation like sense of touch.

Sports movement guidance and rehabilitation for beginners are thought as the activities in which the motion instruction is required. In the actual activities of the motion instruction in the medical and welfare field, physical therapists instruct and explain patients on how to move their body, using gestures for rehabilitation. This instruction/explanation using gestures can support only visual and aural information, and it doesn't include the patients' somatic sensation. But, using therapists' own hands, they can directly move the patients' hands and feet. Even so, the instruction of complex operations that needs multijoint coordinated movement like walking is difficult because the therapist can hold only one place at the same time.

For the purpose of the substitution of target motion by remote-controlled artifact, research on master-slave systems has been performed in the field of robotics and virtual reality. A master-slave system consists of the master system on one side that teaches, and the slave system on the other side to be taught. A typical example of application includes the remote control of a robot hand with a master-slave system. The master-slave systems are also used in extremely difficult environments such as in space, nuclear plants or water. These teleoperated control systems have a merit over local control. A skillful operation on the master side can be transmitted to the machine on the slave side. Moreover, the research on performance upgrade of a remote-operational feeling has also been performed. Its representative research on tele-existence is showed by Tachi [1]. It produces an advanced presence when the operator is in a remote place, and operates the slave.

As for these master-slave systems, the principal objective is put on the achievement of the slave side operation in the remote place. A man operates the master side and the machine operates the slave side. However, the research on a system whose master sides and slave sides are humans has not been done so far. If the operators of the master-slave system are humans, we can expect that an interactive motion instruction would be achived. For instance, a physical therapist guides the ambulation activity of the patient or the sports player teaches the beginner the skill of efficient operation. Moreover, not only the instruction of operation but also perception of the maneuvering feeling on the other side and motion assist of a worker in a remote place are thought of as application examples.

Human support technologies for measuring a variety of biological information that takes part in a human's motion such as angle, angular velocity and torque of the joints have been developed in our laboratory by the use of Cybernics technology that can support, enhance, and expand a wearer's bodily functions [2].

A movement diagnostic system based on objective data is desired, and support with such a system is expected by acquiring and using biological information for rehabilitation. The proposal of an effective rehabilitation training method also becomes possible by the motor function that the robot suit has. Physical therapy continues for a long term comparatively, and monotonous work of walking training with physical assistance of therapist is done as a routine. It seems that it is suitable for this reasons to train in such a field with a device by a technological engineered approach. It is an important development field of Cybernics.

We installed the master-slave system to the HAL in order to accomplish the motion instruction system developed in the present study. The robot suit HAL is a wearable exoskeletal power assist robot aimed at supporting, enhancing, and expanding the wearer's body function. Even if medical staff focusses on the guidance of the motion by hand and teaching

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step by step, the instruction is limited to only a specific joint. However, if the angle and the angular velocity are in real-time transmitted, and if the motion generation is possible according to the control of power units, the system enables controlled motion of multiple joints simultaneously as a method of taking the place of above mentioned conventional methods.

Therefore, the purpose of this research is to develop a motion instruction system by using the telecommunication facility of robot suit HAL. To implement aforementioned functions, this paper contains the following sections. In section 2, we describe the methods of this research, which consist of concept of motion instruction, required specification, system configurations, data communication, an explanation of unilateral and bilateral control and experimental settings. In section 3, the results of the experiment are described. There is a discussion and a brief conclusion in section 4.

II. Methods

A. Concept of motion instruction with interactive robot suit HAL

The robot suit HAL has an exoskeletal structure which covers the wearer's body segments such as waist, thigh, lower thigh and foot part and has joint parts corresponding to the human body, based on embodiment [3], [4]. HAL is one of the research platforms of Cybernics and has a wearer movement monitoring function and a power assist function. For functionality expansion, we installed an interactive function in this two HALs. It becomes possible to construct a motion instruction system timewise and physically by letting HAL communicate mutually. It was named the "interactive robot suit".

As an example instructing exercise to somebody, a doctor teaches it to a patient. In this case, both the patient and doctor wear the HAL. If kinematic information can be interactively exchanged with HAL, the doctor can be able to guide and to teach the walking rehabilitation of the patient, and it becomes possible to transmit the patient's kinematic information to the doctor as an actual movement. The basic concept is shown in Fig. 1. In the interactive communication with HAL, the patient and the doctor exchange each other's kinematic information. By acquisition of the quantitative numerical data from the wearer's HAL, information presentation to the other side becomes possible. When the doctor generates the joint torques to the patient's HAL, the desired joint torques let the patient exercise, and also the doctor can fell the patient's reaction.

B. Required specification

To construct the system of the concept described above, the composition of the system with the exoskeletal robot which provides sensors and power units, and a communication device was needed. A smooth exchange of the composed information on the movement between master-slave is also required.

The interactive function of the HAL consisted of a master-slave architecture. The master-slave is roughly divided into an unilateral control and a bilateral control. The motion instruction system is composed of unilateral instruction and bilateral instruction.

The unilateral control part of the master-slave system is composed of only communication from the master side to the slave side. The side which is used for teaching is made a master, and the side which is being taught is made a slave. Because it is a system where deviation with the slave is not fed back to the master side, the slave side will do tracking control in which the targeted value is the movement of the master side. When the motion is instructed, it becomes possible to teach the coordinated movement the multiple joints through not only sight and aural but also somatic as a new modality. When a teacher teaches the beginner the swing motion such as golf and tennis, the taught person relaxes, and the teacher holds the hand of the taught person to give a guidance of the specific motion. It is thought that unilateral motion instruction is useful when the movement is entrusted to the teacher and it is used at the early stage of the learning process of the movement in which the taught person relaxes.

In bilateral control, system deviation with the slave is fed back to the master. Therefore, the master can feel how much the posture of the slave is shifted. Moreover, the movement gap between the slave HAL, worn by the person being taught, and the master HAL can now be felt by the doctor at each joint.

When the functionality of an interactive movement instruction system is built into a HAL system, we gains the following.

- Monitor of angles of joints
- Mechanical impedance compensation of the HAL (mechanical impedance of the HAL is calculated by identifying the parameter)
- Transmitting power to segment of the wearer and to cause movement
- Data communication.

C. System configurations

Here we explain the composition of HAL for the movement instruction system. Fig. 2 shows an overview of HAL system configurations. The exoskeleton part is composed of power units, frames and molded plastic equipments. Power units are attached on each hip and knee joint, and actuate each joint by their torques. They can also produce a negative assist torque, which can be used for activities like weight training as a counter torque. The exoskeletal flames are fixed to the wearer's legs with fastening equipments made of molded plastic. It is possible to change the length of the thigh and lower thigh frame and transmit the torques from the power units to the wearer's legs. There are angular sensors to measure the motions of HAL. Torque data is estimated based on the amount of current provided to each power unit. Moreover, it is a complete wearable system because batteries and wireless LAN are installed. There is no need to supply energy from the outside, such that HAL can move independently.

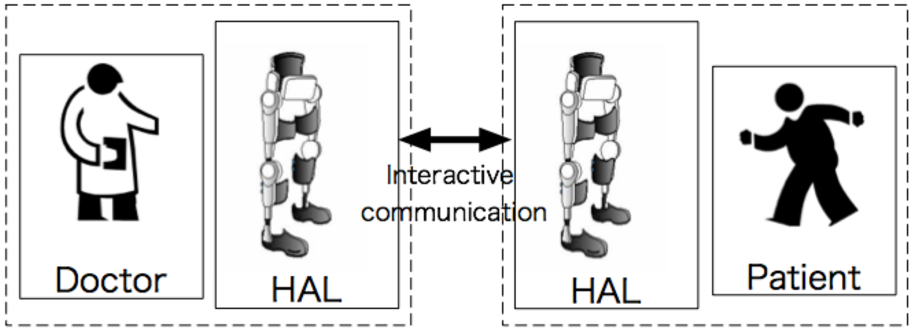

Fig. 1. Basic concept of this research.

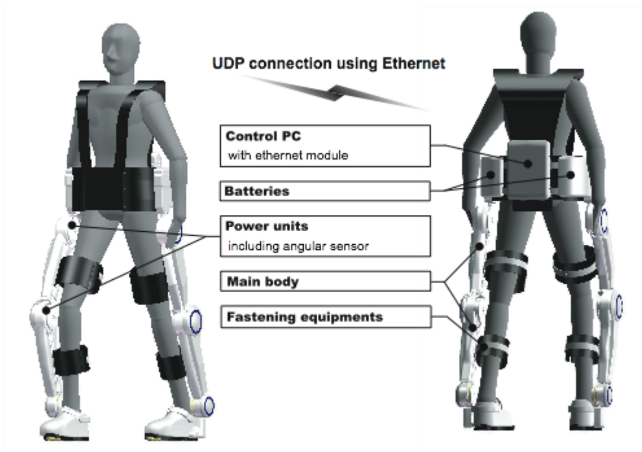

Fig. 2. System configurations.

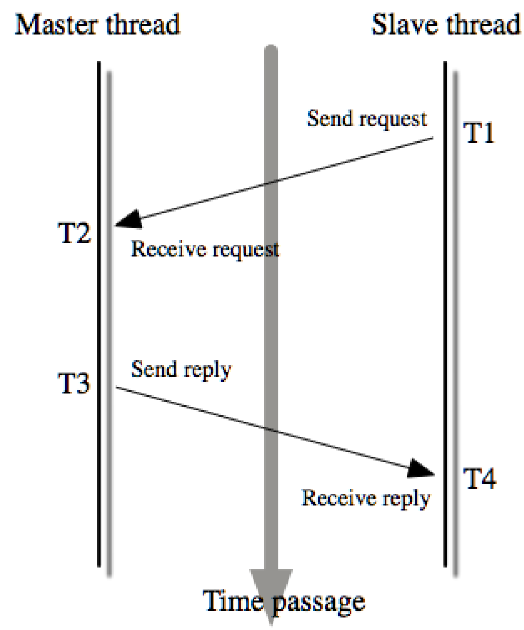

Fig. 3. Synchronized algorithm.

D. Data communication for interactive robot suit HAL

Because HAL has a telecommunication facility using ethernet device, an interactive rehabilitation system can be constructed using two or more HALs. The slave-HAL wearer gets instructed about the angle displacement of the master-HAL wearer. Moreover, the master-HAL wearer gets instructed about the angle displacement of the slave-HAL wearer so as to construct an interactive (bidirectional) motion instruction system with each other. 1)First of all, kinematic information measured with the HAL (HAL-A) is sent to another HAL (HAL-B). 2) In HAL-B, the power units are driven by the output torque that is decided based on the deviation between the signal that has been sent from HAL-A and the measured signal in HAL-B. 3) Kinematic information of HAL-B is sent to HAL-A, and is used to control HAL-A.

The control program uses multithreading so that each control computer can do the control of the hardware and the communication at the same time when a bidirectional interactive system is constructed.

The protocol used to make the interactive communication network was TCP/IP. There are two kinds of transport protocols in TCP/IP 1) TCP(Transmission Control Protocol) and 2) UDP(User datagram Protocol). UDP was adopted instead of TCP because UDP has short transfer stop time and also shorter data reception compared to communication by TCP. UDP is connectionless and doesn't confirm whether the data has reached the other side or not. The transmitting side just transmits the data and the receiving side picks up the data. It makes no amends for the loss of packets and the order of data, and does not confirm reception, thus allowing no limit in transfer time on the network.

When communicating with two or more HALs, one has to synchronize a counter in the control program between the HALs when evaluating various measurement data at the same time to verify the performance. The outline of an algorithm that uses synchronization is shown in Fig. 3. The slave has four parameters: $T1$ and $T3$ are transmission times, and $T2$ and $T4$ are reception times. Using this information, the one way communication time to carry a packet is defined as T_{half} and the time lag as T_{lag}

$$(T2-T1) = (T_{half}) + T_{lag} \tag{1}$$

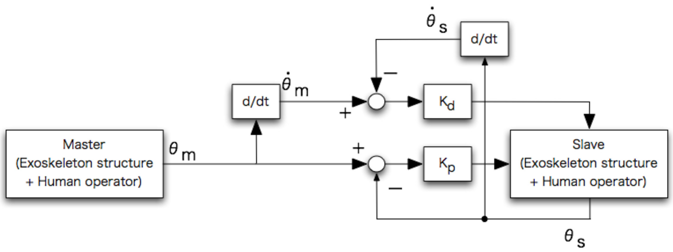

Fig. 4. Unilateral angular teaching.

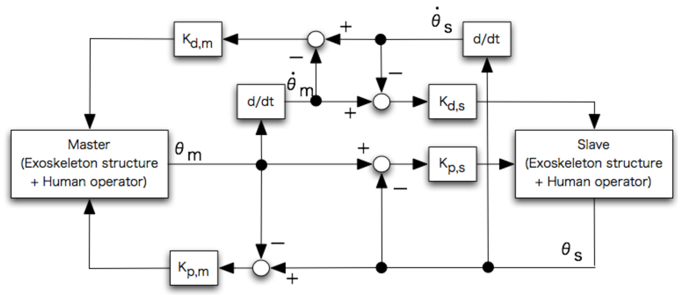

Fig. 5. Bilateral angular teaching.

$$(T4 - T3) = (T_{half}) - T_{lag} \tag{2}$$

Here, assuming that T_{half} of transmission and T_{half} of the reception is the same

$$T_{lag} = \{(T2 - T1) - (T4 - T3)\}/2 \tag{3}$$

When the initial state is the time lag state between the master-HAL and the slave-HAL, the procedure to revise the lag and achieve synchronism is as follows:
1.Transmission time $T1$ of the slave side is measured, and it is transmitted to the master.
2.Receipt time $T2$ of master is measured.
3.Transmission time $T3$ of the master side is measured, and is transmitted to the slave.
4.Reception time $T4$ is measured on the slave side.
5. The time lag is calculated from the time obtained from 1 to 4.
6. Slave's clock is corrected.

It is not possible for these assumptions to be correct all the time. However if the value is small its influence can be ignored. It depends on communication environment but even if there is large delay it will remain within the a few milliseconds if the ethernet connections are in the same network. In this research synchronism was achieved using above-mentioned T_{lag}.

E. Unilateral and Bilateral control

Unilateral control is a method to compose the master-slave system by the communication only for one from the master side to the slave side (Fig. 4). In unilateral, slave will compulsorily do the movement similar to the master. If deviation grows, a bigger instruction torque is generated by the feedback control, and a torque will be received from HAL in the direction in which the master is followed if starting resisting.

In bilateral control, the instruction torque to the slave is according to (5), and the torque to the master follows (4). The slave torque is opposite in sign to the master torque when deciding K_p and $K_d > 0$. The central feature of the bilateral instruction is to sense and correct any small difference between the master and slave wearer, which will enable the wearers to learn target motions at a higher level of detail and precision. We believe this method is suitable for rhythmic or repetitive exercises or those where timing of the motion is essential. The control torque for the motion instruction is determined using the following block diagrams in Fig. 4 and Fig. 5. For this bilateral master-slave system it was decided that the doctor was on the master side and patient was on the slave side.

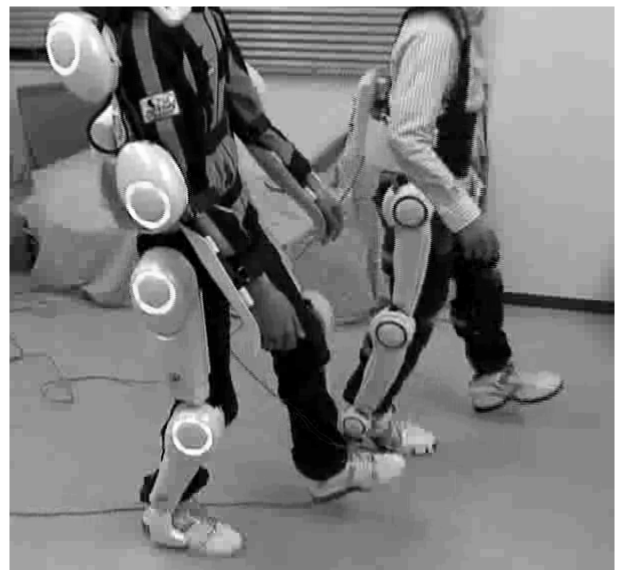

Fig. 6. Experimental overview.

The doctor as the master side receives τ_{master} from the master-HAL as follows:

$$\tau_{master} = K_{p,m}(\theta_s - \theta_m) + K_{d,m}(\dot{\theta}_s - \dot{\theta}_m) \tag{4}$$

$K_{p,m}$ and $K_{d,m}$ are respectively the master's feedback gains of angle and angular velocity.

The patient receives τ_{slave} from the slave-HAL as follows:

$$\tau_{slave} = K_{p,s}(\theta_m - \theta_s) + K_{d,s}(\dot{\theta}_m - \dot{\theta}_s) \tag{5}$$

$K_{p,s}$ and $K_{d,s}$ are respectively the slave's feedback gains of angle and angular velocity. The angle and the torque are positive when the joint flexes and the joint extends. The angle is 0 [rad] in the straight leg position. The torque is 0 [Nm] when there is no output. The drive torque is generated according to (4) and (5), and corrected to match the doctor's angle and angular velocity for the patient when there is a deviation in the angle or the angular velocity.

F. Experimental settings

The experiments were conducted in an environment as shown in Fig. 6. An ambulation exercise was chosen for this experiment, as it is a part of rehabilitation. HAL-5 FB (full body version of HAL-5) was used as the master-HAL and HAL-5 LB (lower body version of HAL-5) Type-C as the slave-HAL.

In this research, proportional and derivative (PD) control was applied to a reference tracking control and used as an angular servo for each joint. In earlier research in our laboratory on a walking support for patients with a handicap in their lower limbs, angular trajectories of the hip and knee joints during walking motion were used as the control reference. From this research, we could use the PD gains, which were investigated to correspond to the wearer's bodily parameters [5].

The purpose of the experiment is as follows. For unilateral control, to confirm whether the instruction torque to the slave-HAL follows the control law, and to confirm whether the motion of the slave follows the master-HAL motion in accordance with the deviation of the angle of the joint. In bilateral control, to confirm whether each instruction torque to the master-HAL and slave-HAL follows the control laws, and to confirm whether the deviation between the angles of similar joint of two walking people with the same motion intention can be quantitatively measured.

III. Results

A. Unilateral motion instruction

The purpose of the unilateral motion instruction and its operating principle was explained to the slave-HAL wearer beforehand and he was asked to exert only minimum force that is enough to maintain his balance. Fig. 7 shows the joint angles of the master-HAL and the slave-HAL, and output torque of the slave-HAL for the hip joint and knee joint while walking during the unilateral motion instruction: (a) is the left leg and (b) is right leg. The output torque is the motion-instruction torque to the wearer of the slave-HAL. This is the data of four consecutive steps in the middle of continuous walking. Right leg steps at t = 0 [sec] followed by the left leg and so on. Depending on the deviation the input torque to the slave-HAL was found to be smaller at the support phase and larger at the swing phase. Furthermore, as a whole it was confirmed that the master was making the first move. As a result, the instruction torque to the slave-HAL was generated based on (5) with the intention to follow the motion of the master-HAL. The upper graph in (a) explains the feedback control of the servo angle as an example of the motion of the left hip joint. At t = 1.5 [sec] to t = 2.0 [sec] and t = 5 [sec] to t = 6.0 [sec] (approximately) are periods of left hip joint flexure. The flexure starts after the hip joint angle of the master heads the hip joint angle of the slave. We were able to confirm that the hip joint flexure of the slave was produced after the instruction torque for the slave-HAL is generated and accepted by the slave-HAL. Based on unilateral motion instruction we confirmed that the left and right waist, and knee joint of the slave were controlled so as to follow the motion of the master. We also confirmed that the instruction torque for the slave-HAL was generated corresponding to the incoherent motion of the slave with the master. We confirmed that the instruction torque in the swing phase was generated above a certain value due to incoherent motion, however, a very small instruction torque was generated in the support phase due to an almost coherent motion. Through this experiment execution of unilateral motion instruction under consecutive walking was confirmed.

B. Bilateral motion instruction

The purpose of the bilateral motion instruction and its operating principle was explained to both the master-HAL wearer and the slave-HAL wearer beforehand. The wearer of the slave-HAL was instructed to synchronize his motion with that of the master-HAL as much as possible. Fig. 8 shows the joint angles and output torque of both the master-HAL and the slave-HAL for the hip joint and the knee joint when the bilateral motion instruction experiment was performed for walking motion: (a) is the left leg and (b) is the right leg. The output torque is the motion instruction torque to the wearer of HAL. This is the data of three consecutive steps in the middle of continuous walking. Right leg steps at t = 0 [sec] followed by the left leg and so on. It was found that the amount of instruction torque calculated depending on the deviation of joint angles was generated as a whole in smaller amounts in the support phase (joint angle extension or joint angle maintenance phase), and larger in the swing phase (joint angle flexure phase). The instruction torque to the slave-HAL was generated based on (5) with the intention to follow the motion of the master-HAL. The instruction torque to the master-HAL was generated based on (4) and was confirmed to be in accordance with the incoherency of the motion with the slave. The wearer of the master-HAL felt this torque both as restive and assistive. The upper graph in (a) explains the feedback control of the servo angle as an example of the motion of the left hip joint. At t = 1.5 [sec] to t = 2.0 [sec] and t = 5 [sec] to t = 6.0 [sec] (approximately) are periods of left hip joint flexure. The instruction torque for the slave-HAL is generated when flexure starts after the hip joint angle of the master heads the hip joint angle of the slave. We were able to confirm that this torque is equal in amount but opposite in sign to the instruction torque generated for the master-HAL. Based on bilateral motion instruction we confirmed that the left and right waist, and knee joint of the slave were controlled so as to follow the motion of the master and the slave control of the master was performed vice versa. We also confirmed that the instruction torque for the slave-HAL was generated corresponding to the incoherent motion of the slave with the master. Regarding the leg's upswing, the instruction torque was confirmed to be due to the deviation caused by lagging behind of the slave with respect to the master by a few hundred milliseconds. Regarding other motions, almost synchronized joint movement was performed with a small instruction torque of almost 0 [Nm]. Through this experiment execution of bilateral motion instruction under consecutive walking was confirmed.

IV. Discussion and Conclusion

In unilateral motion instruction, the slave-HAL's right and left knee joint followed the master-HAL at almost the same timing and same amplitude, whereas the hip joints had some errors between the slave-HAL and the master-HAL. Considering the hip joint, the wearer of the master-HAL intended to let the slave go onward, and then the master-HAL bent its hip joint more than normally required.

In bilataral motion instruction, nearly synchronic joint movement was seen all through the data. The walking pattern of the master-HAL's wearer and the slave-HAL's wearer was natural like a healthy person's pattern. When a slight delay was present in hip joint swing, the slave followed the master. At that time, the master felt the instruction torque as a negative sign torque which meant a sense of resistance.

There are many possibilities for this system. Combination with information presentation by graphical user interface. Statistical data analysis of synchronous pattern of cyclic movement. An interactive system could be created using mutual communication between two HALs as in Fig. 1. Interactive here means bidirectional, live and real-time, and creating a synergy effect. The doctor and the patient, connected through the network of HAL, exert an influence of kinematic information to each other bi-directionally. Their motion information is presented directly to each other in real-time. The virtual but physical bond, as if two people's legs were softly but closely bond together, created by this system of two HALs realizes a new man-machine system which enables the sharing of each other's somatic sensation by synergistic motion information feedback. It thus becomes a motion instruction system.

The measured wearer's kinematic data was mutually communicated between the master and slave HAL. As the basic system to achieve this, in the unilateral and bilateral motion instruction experiments, the effectiveness of the basic motion instruction system was confirmed using normal ambulation.

This HAL was made as a platform, the function was enhanced, an interactive function was installed, and the motion instruction system was developed. This was possible using the telecommunication facility of robot suit HAL, and made interactive by sending to each other the measured kinematic data.

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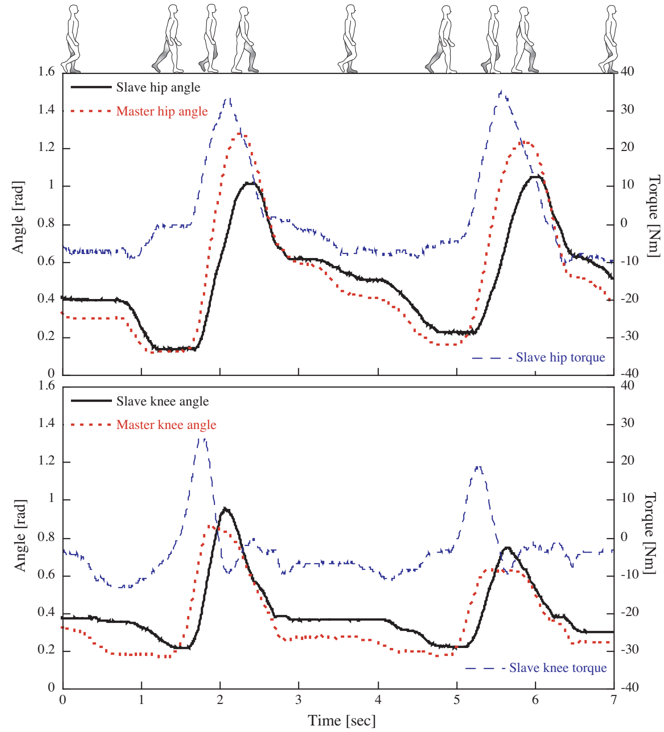
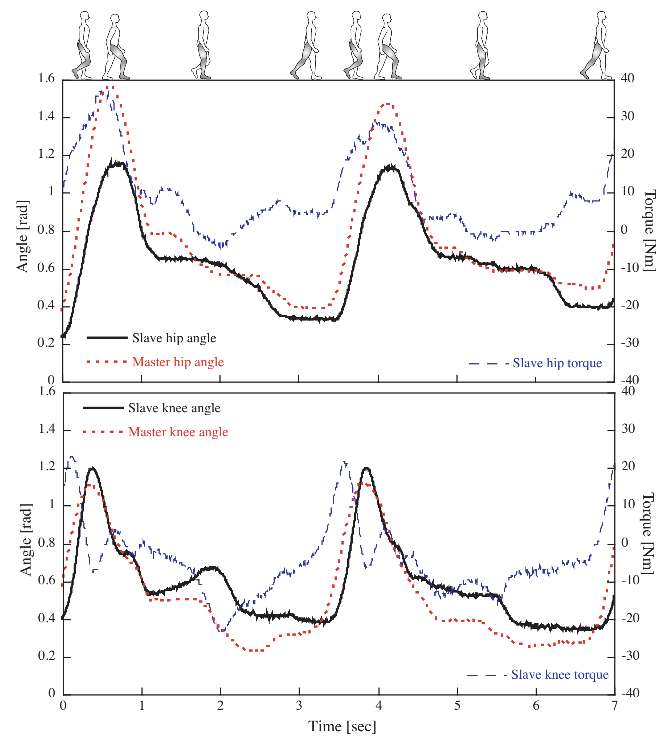
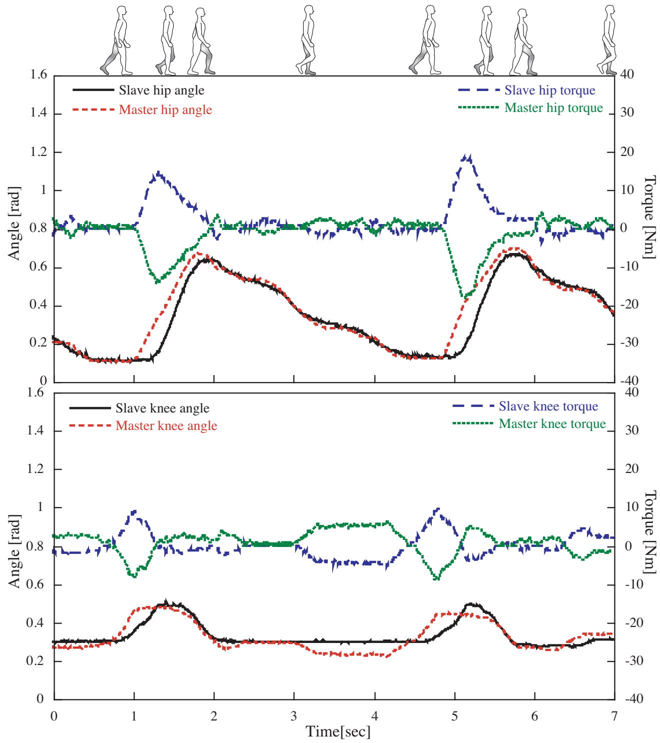


(a) Left leg.

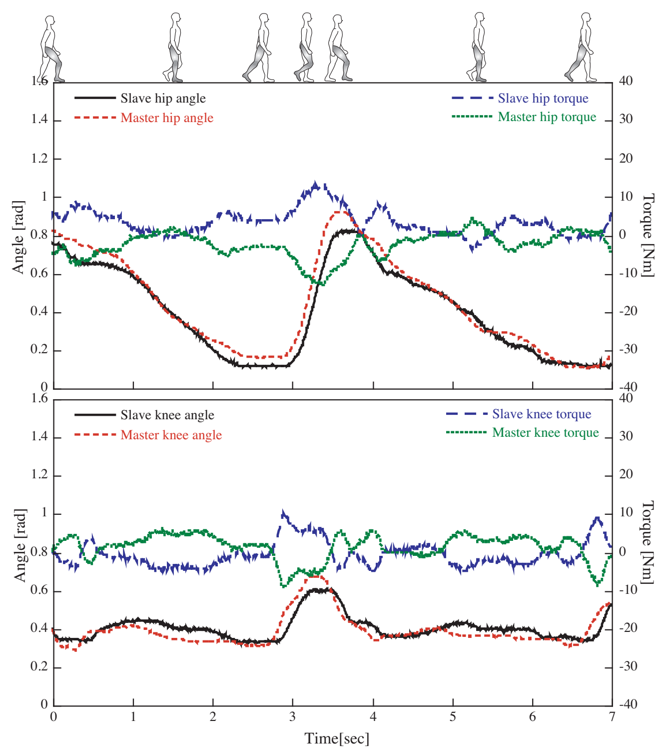


(b) Right leg.

Fig. 7. Slave's hip and knee joints follow the master's angles as reference in almost part of time except bending act in two cycles of the walking motion instruction. (a) Slave left leg joint angles, reference master left leg joint angles and power units' torques. (b) Right leg joint angles, reference master right leg joint angles and power units' torques.



(a) Left leg.



(b) Right leg.

Fig. 8. Hip and knee joints follow the each other's angles in almost part of time in two cycles of the walking motion instruction. (a) Slave left leg joint angles and power unit's torques, and master left leg joint angles and power units' torques. (b) Slave right leg joint angles and power unit's torques, and master right leg joint angles and power units' torques.

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