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Development of a Hand Motion Assist Robot for Rehabilitation Therapy by Patient Self-Motion Control

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***Abstract*— This paper presents a new hand motion assist robot for rehabilitation therapy. The robot is an exoskeleton with 18 DOFs and a self-motion control, which allows the impaired hand of a patient to be driven by his or her healthy hand on the opposite side. To provide such potential that the impaired hand is able to recover its ability to the level of a functional hand, the hand motion assist robot is designed to support the flexion/extension and abduction/adduction motions of fingers and thumb independently as well as the opposability of the thumb. Moreover, it is designed to support a combination motion of the hand and the wrist. The design specifications and experimental results are shown.**

I. Introduction

The number of patients with a disability in a certain part of the body as a result of a cerebral vascular accident (CVA) or bone fracture is increasing in step with the aging of the population in Japan. These patients need timely and persistent rehabilitation to recover their lost abilities and regain their normal daily lives. Long rehabilitation training sessions with therapists, who are in relative shortage, are not always possible for patients to obtain. A solution to this problem would be a rehabilitation system that allows the patient to carry out rehabilitation exercises by him or herself.

Many systems for rehabilitation have been studied. Functional electrical stimulation (FES) [1], [2] has proven to be a valuable tool in the restoration of arm function to patients, but this approach is not suitable for patient self-controlled rehabilitation therapy. Many aspects of robotic arm rehabilitation therapy [3]-[5], including clinical tests [6], [7], have been reported. Most disabilities caused by CVAs are hemiplegic; that is, only one hand is impaired. Arm rehabilitation therapy with the aid of a robot [8], which involves bimanual, mirror-image, patient-controlled therapeutic exercises, is one type of self-controlled rehabilitation.

On the other hand, hand rehabilitation is somewhat difficult because the hand possesses many degrees of freedom of motion, and a hand motion assist device that could be attached is small in size. Research on the function of the fingers by FES [9], [10], hand rehabilitation devices [11] - [15], virtual reality-based stroke rehabilitation [16], and tele-rehabilitation [17], [18] have been presented. Therapies using previously proposed robotic devices for hand rehabilitation provide self-controlled rehabilitation, but these therapies are limited to hand motions such as gripping and tapping because these devices assist only flexion/extension of the thumb and fingers and cannot assist the abduction/adduction and thumb opposition motions. To enhance the quality of life of patients with hand impairments, a rehabilitation therapy for manipulation function and fine motions such as turning knobs or handling chopsticks is needed [19]. In hand rehabilitation, a robotic device is required to assist not only the flexion/extension but also abduction/adduction motions of each joint of the fingers and thumb independently. Another major requirement for such a device is to assist the motion of thumb opposition because the dexterous manipulation of objects by humans requires thumb opposability. Moreover, the palmar flexion/dorsiflexion of the wrist and the pronation/supination of the forearm have important roles in manipulation functions and fine motions [19].

We have developed a two-finger exoskeleton device that assists the flexion/extension and abduction/adduction of MP and PIP joints, and we have reported a clinical test of it involving self-controlled rehabilitation therapy [20]. Moreover, we have developed a hand exoskeleton device that assists the joint motions of four fingers and a thumb [21]. The hand exoskeleton device, however, does not adequately provide the needed thumb opposition. In order to recover an impaired hand to the level of a functional hand, a motion assist device should support thumb opposability.

This paper presents a newly developed hand motion assist robot with 18 DOFs for self-controlled rehabilitation therapy by patients that supports not only the flexion/extension and abduction/adduction motions of each joint in the hand but also thumb opposability. Moreover, it assists the palmar

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flexion/dorsiflexion of the wrist and the pronation/supination of the forearm. Design specifications and experimental results of this robot are presented.

II. Design of The Mechanism

A. Design concept

During hand rehabilitation, a therapist extends and flexes each finger joint independently over its movable area many times. What is required as a substitute is a device to assist such independent finger motions. There are three joints in each finger, i.e., the metacarpophalangeal (MP), proximal interpharangeal (PIP), and distal interphlangeal (DIP) joints. In light of the needs in the field of hand rehabilitation, the functions required to a finger rehabilitation device are motion assistance for the flexion/extension of the MP and PIP joints and for the abduction/adduction of the MP joint since the DIP joint moves indirectly together with the PIP joint.

The thumb also has three joints, i.e., the carpometacarpal (CM), metacarpophalangeal (MP), and interpharangeal (IP) joints, each of which moves independently. For the thumb, the function required in a rehabilitation device is motion assistance in the flexion/extension of the CM, MP and IP joints and in the abduction/adduction of the CM joint. Moreover, motion assistance for thumb opposition is strongly required. In addition to independent finger motion assistance, we took the following requests into consideration in the design of the robot:

- Coordination with wrist motion
- Securing the required movable range of joints and the maximum joint torque
- Flexibility with various hand sizes and easy attachment
- Safety in case of a sudden failure

To satisfy these requirements, we have created a form of a hand motion assist robot as an exoskeleton with 18 DOFs. It consists of four finger motion assist mechanisms, a thumb motion assist mechanism and a wrist motion assist mechanism. Its applicable hand size is based on statistics about the Japanese hand size [22] and movable joint ranges, as referenced in a document [23].

An experienced therapist determined the required joint torques, and we measured them using a measurement device, as shown in Fig. 1. The therapist extended and flexed a lever

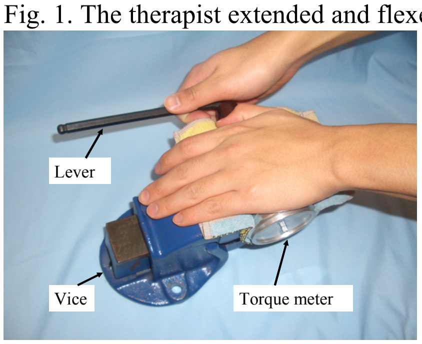


Fig. 1. Method for measuring the maximum joint torque by therapist

TABLE 1
Design Specifications Of Had Motion Assist Robot

Finger	Number of fingers			4
	DOF			3
	Movable range (deg)	MP joint	Extention/Flexion	0 - 90
			Adduction/Abducti	0 - 45
		PIP joint	Extention/Flexion	0 - 100
	Maximum torque (Nm)	MP joint	Extention/Flexion	0.29
			Adduction/Abducti	0.16
		PIP joint	Extention/Flexion	0.29
Thumb	DOF			4
	Movable range (deg)	CM joint	Extention/Flexion	0 - 90
			Adduction/Abducti	0 - 60
		MP joint	Extention/Flexion	0 - 60
		IP joint	Extention/Flexion	0 - 80
	Maximum torque (Nm)	CM joint	Extention/Flexion	0.3
			Adduction/Abducti	0.3
		MP joint	Extention/Flexion	0.26
		IP joint	Extention/Flexion	0.26
Hand holding part	Adjustable range (mm)	Anteroposterior direction		32
		Heightwise direction		20

TABLE 2
Design Specifications Of Wrist Motion Assist Mechanism

DOF		2
Movable range (deg)	Pronation/Supination	-90 - 90
	Palmar flexion/Dorsiflexion	-90 - 70
Maximum torque (Nm)	Pronation/Supination	3.1
	Palmar flexion/Dorsiflexion	1.3

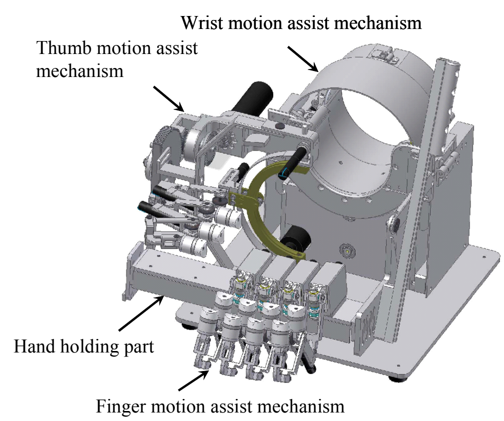


Fig. 2. Hand motion assist robot

(considered to represent a patient's finger) with the required maximum torque. The design specification of the hand motion assist mechanism is shown in Table 1.

In rehabilitation therapy for manipulation function and fine motions such as turning knobs and handling chopsticks, the palmar flexion/dorsiflexion motion of the wrist and the pronation/supination of the forearm should be assisted in coordination with the hand motion. We call this part a wrist assist mechanism. The required joint torques of the wrist mechanism were measured in the same way as was the finger joint torque. The design specifications of the wrist motion assist mechanism are shown in Table 2.

The hand motion assist robot is designed to satisfy the above specifications. A designed hand motion assist robot is shown in Fig. 2. The details of the mechanism are explained in the following sections.

B. Finger motion assist mechanism

A finger motion assist mechanism is constructed as an ex oskeleton of a finger, as shown in Fig. 3. This exoskeleton permits various finger sizes because an active joint axis of the mechanism does not have to coincide with the finger joint axis of a human hand. This mechanism assists the flexion/extension of the MP and PIP joints and the abduction/adduction of the MP joint. There are three servo motors with rotary encoders. The first and second servo motors assist the two-DOFs motion of the MP joint through a differential gear. The third motor assists the flexion/extension of the PIP joint. The finger motion assist mechanism forms two closed loops with the human finger, in which the first and second fixtures are attached to the proximal portion and middle position of human finger, respectively, and the finger joint motion of human is assisted independently. To measure the finger joint torque, a 3-axes force sensor is mounted on each fixture. Details of this mechanism are presented in the reference [21].

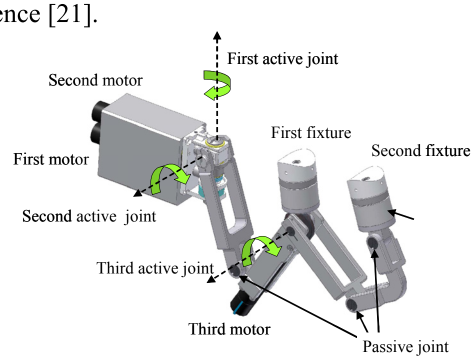
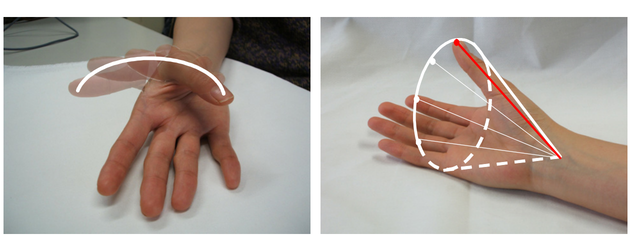


Fig. 3. Finger motion assist mechanism

C. Thumb motion assist mechanism

A human thumb has IP, MP, and CM joints that generate the flexion/extension of the thumb. Moreover, the CM joint generates the abduction/adduction and thumb opposition motions simultaneously, as shown in Fig. 4 (1). This thumb opposition is necessary for human dexterous object manipulation, but it is difficult to assist such motion by the above-mentioned finger motion assist mechanism. It can be assumed that the thumb opposition is a circular cone motion, as shown in Fig. 4 (2), in which the tip of the cone is located in the wrist and the orientation of the thumb is almost constant with respect to the cone center axis. Hence, the abduction/adduction and flexion/extension motions of the CM joint are homologized, respectively, to the circular cone motion and a vertex angle motion, which adjusts the vertex angle of the cone. The combination of these cone motions assists the CM joint motions. A robotic device assisting thumb opposition has never been addressed.



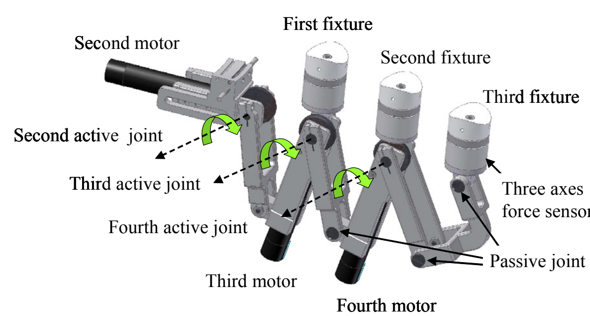
(1) Thumb opposition (2) Circular cone motion

Fig. 4. Opposability of the thumb

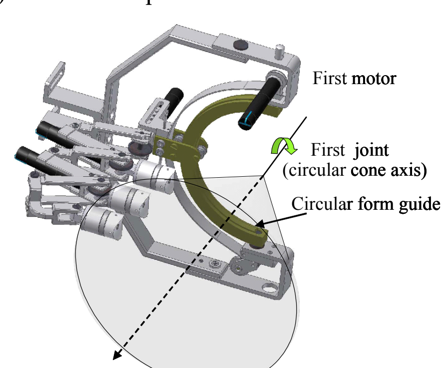
A designed thumb motion assist mechanism is shown in Fig. 5, in which (1) shows the part that assists the flexion/extension of the thumb. There are three servo motors with a rotary encoder which assist the flexion/extension of the IP, MP, and CM joints independently. The mechanism forms three closed loops made by the human thumb, involving the first to third fixtures being attached to the proximal to distal positions of the human thumb, respectively. To measure the joint torque of a human thumb, a 3-axes force sensor is mounted on each fixture. Fig. 5 (2) shows a part which generates a circular cone motion to assist the thumb opposition. We adopted a circular form guide because the tip of the cone is located in the human wrist. The first servo motor drives the flexion/extension assist mechanism on the surface of the circular cone to make a circular cone motion and thereby assists the human thumb opposition.

D. Hand-holding part

In our mechanical design, the average hand sizes of fingers and thumbs were based on statistical data about Japanese hands [22]. However, it is necessary that the hand motion assist robot can be applied to various hand sizes as much as possible. To respond to different finger sizes, the positions of



(1) Motion assist part of extension and flexion



(2) Motion assist part for thumb opposition

Fig. 5. Thumb motion assist mechanism

the finger and thumb motion assist mechanisms can be shifted not only anteroposteriorly but also heightwise on the hand-holding part. Adjustable ranges are 32 mm anteroposteriorly and 20 mm heightwise. This permits most Japanese adults to use the hand motion assist robot for hand rehabilitation therapy.

E. Wrist motion assist mechanism

The human wrist exhibits three different motions: palmer flexion/dorsiflexion, pronation/supination and abduction/ adduction. In hand rehabilitation therapy, the first two motions are weighted because the object manipulations such as placing a peg in hole or turning a knob—used in daily life frequently—require motion that is coordinated with palmar flexion/dorsiflexion and pronation/supination of the wrist. Therefore, these two joint motions are supported by the hand motion assist robot (shown in Fig. 6), in which the first and second joints correspond with the pronation/supination and palmar flexion/dorsiflexion motions. The two joint axes are orthogonal to each other, and each actuator is a servo motor with a rotary encoder. A counter balancer rotating around the second joint axis is set to keep a weight balance with the finger and thumb motion assist mechanisms, which rotate around the second joint axis. The design specifications of the wrist motion assist mechanism are shown in Table 2, in which numerical values are obtained by the same way as those for the finger motion assist mechanism.

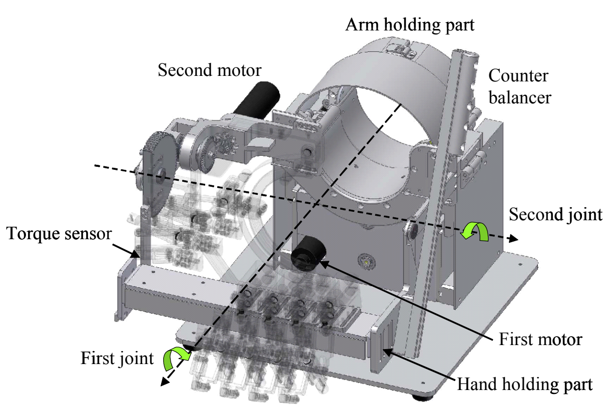


Fig. 6. Wrist motion assist mechanism

F. Fixing of hand and arm

The forearm and hand of a patient are attached to the hand motion assist robot as shown in Fig. 7. The patient's impaired hand, wearing a glove, is placed on the hand-holding part and is fixed by Velcro straps attached to the finger fixture. In order to allow easy desorption and height mobility, the backside of the glove is air through, and the front side is a large-scale mesh, as shown in Fig. 8. The forearm is attached with a cuff and is fixed by an arm-holding part. Various sizes of arm can be accommodated by modifying the air pressure of the cuff.

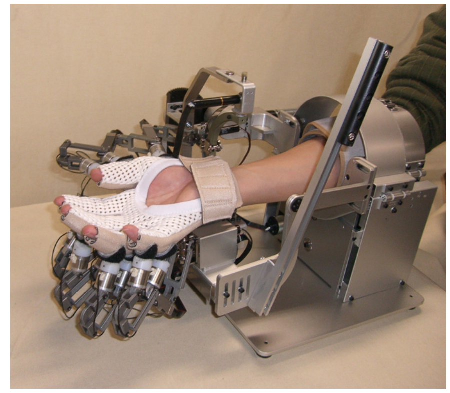


Fig. 7. A human hand fixed in the hand motion assist robot

(1) Back side (2) Palm side

Fig. 8. Glove on the impaired hand

III. CONTROL SYSTEM

A. Self-motion control

Most patients who need hand rehabilitation are disabled only on one side of the body. With that in mind, we have developed a self-motion controlled hand motion assistance device [20]. The normal patient hand produces the reference motion for the exercise, while the motion assistant device attached to the disabled hand reproduces the motions, thus enabling the impaired hand to make the reference motions symmetrically, as shown in Fig. 9. The self-motion control for arm motion has been presented in [8], and the actual recovery of shoulder and elbow functions in clinical tests has been reported. However, this control method has not been realized for fine hand movement with many DOFs.

The self-motion control will bring the following advantages to the hand rehabilitation:

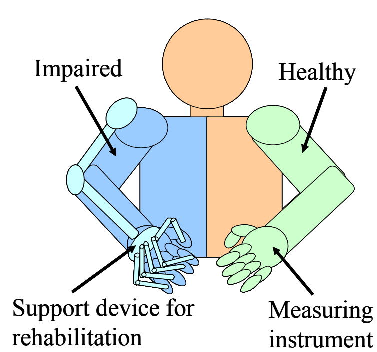


Fig. 9. Self-motion control

- Patients can imagine training motions for an impaired hand because such motions are generated by their own hand on the opposite side. This ability is expected to facilitate the recovery of the disabled function.
- Patients control the motion assist device by themselves. Thus, they can stop the device assistant whenever they want, e.g., if they feel pain during the exercise.
- The motion assistant device is unlikely to force the impaired hand to extend or flex beyond the movable ranges. This is because the reference motions for the impaired hand are constructed from the actual joint angles of the healthy hand since the two hands would be similar in size and structure.
- The master motion of the normal side prevents the atrophy of unused muscles on that side; such atrophy would occur even in a normal hand if not used sufficiently [24].

It is reported that a hand rehabilitation therapy called mirror therapy [25] has a restorative effect. In it a patient sees healthy hand motion through a mirror and feels the impaired hand move with the normal hand. Self-motion control by a patient is expected to have an effect similar to the mirror therapy.

B. *Control equipment*

The control equipment consists of a motor controller and a display system as shown in Fig. 10. The motor controller oversees 22 servo motors in the hand motion assist robot. The operating system of the control CPU is a real time OS (ART-Linux). The display system has two functions: one is to measure the joint angles of the healthy hand by using a data glove (Cyber Glove, by Immersion Inc.) with a measuring period of 10 ms, and the other is to display an exercise menu, useful patient personal information such as the permissible joint motion range, archival records, and so on. The control CPU receives the reference joint angles from the display system through TCP/IP communication. The joint angles of the impaired hand are controlled by a PD control. Sampling time is 1 ms.

C. *Security feature*

The following safety features have been adopted:

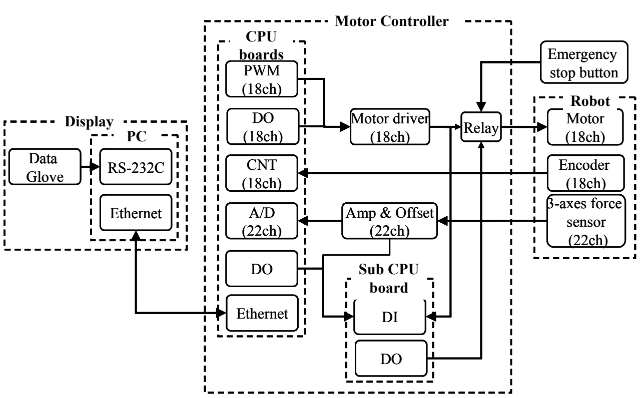


Fig. 10. Control equipment

- Two emergency stop buttons — one for the operator, the other for the patient — are included.
- Sensor fault detection by a force sensor, and torque sensor is carried out periodically.
- Status supervision of all joint angles and joint torques is also carried out periodically.
- An output-limiting facility to adjust the maximum joint torque was added to the motor driver.
- To enhance the reliability of the controller, a sub CPU which keeps watching on the states of sensors, joint torques and the control CPU was added. The control CPU also watches the sub CPU. If a state is abnormal, the output of motor driver is blocked.

IV. DEVICE PERFORMANCE

A. *Frequency characteristics*

Frequency characteristics were measured by the PD control to evaluate the responsibility of the hand motion assist robot. To measure frequency characteristics as a linear system, the amplitude of the sinus signal is 1 degree. Fig. 11 shows the frequency characteristics of the finger motion assist mechanism. (1) is the abduction/adduction of the MP joint, (2) is the flexion/extension of the MP joint, and (3) is the flexion/extension of the PIP joint. In order to dissipate the effect of gravity, each joint axis was set in the gravity direction. Moreover, a dummy hand having flexible finger joints was attached to the hand motion assist robot to maintain a closed loop and avoid free motion by a passive joint. Bandwidths of (1), (2), (3) are about 2.5, 5.0, and 2.5 Hz, respectively.

Fig. 12 shows the frequency characteristics of the thumb motion assist mechanism. (1) is the abduction/adduction of the CM joint, (2) is the flexion/extension of the CM joint, and

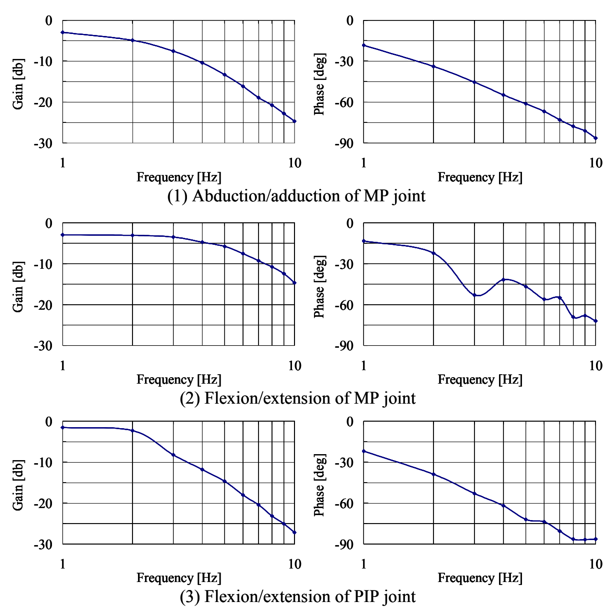


Fig.11. Frequency characteristics of the finger motion assist mechanism

(3) is the flexion/extension of the MP joint. Bandwidths of (1), (2), (3) are about 7.0, 2.5, and 3.5 Hz, respectively. The bandwidths are deteriorative according to the amplitude of the sinus signal because of the limitation of the joint torque.

B. Joint angle responses

To examine the tracking property, joint angle responses are measured as shown in Fig. 13. Fig. 13 (1) shows the joint angle responses of the finger motion assist mechanism; Fig. 13 (2) shows those of the thumb motion assist mechanism. The reference trajectory is given as fifth-degree of polynomial in time, in which the joint angle changes from 0 rad to 0.5 rad with a motion time of 0.5 s. The trajectory errors of these except for the abduction/adduction of the thumb are negligible. The motor of abduction/adduction of the thumb will be changed to a high-performance motor.

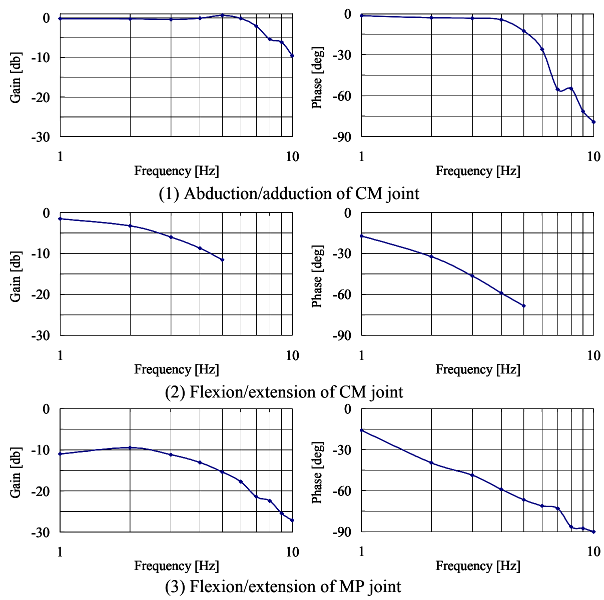


Fig. 12. Frequency characteristics of the thumb motion assist mechanism

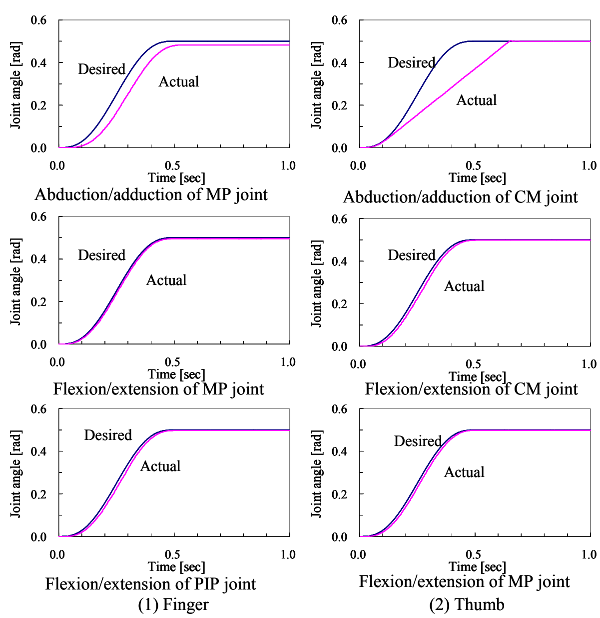


Fig.13. Joint angle responses

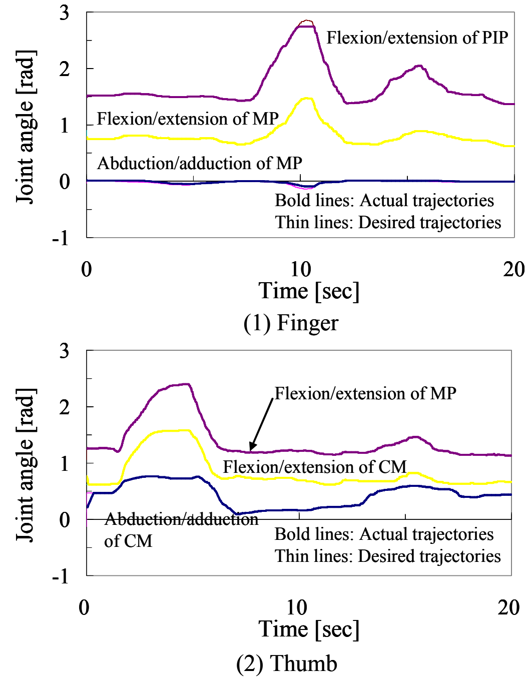


Fig.14. Joint angle responses by the self-motion control

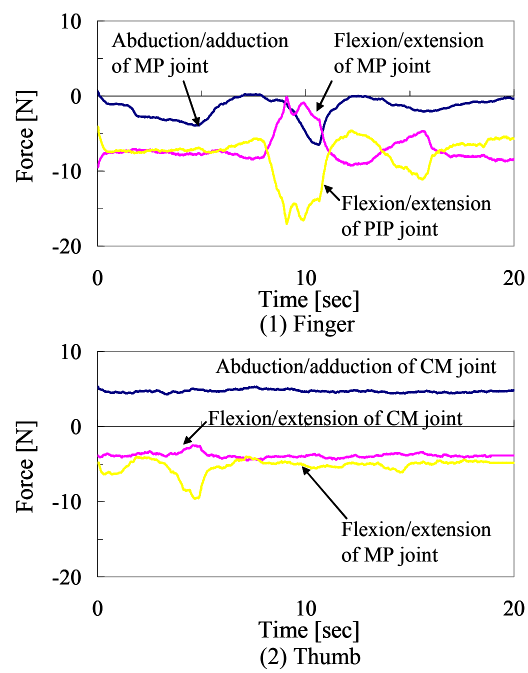


Fig.15. Joint torque responses by the self-motion control

C. Experiment of self-motion control

To evaluate the possibility of robot therapy by a patient's self motion control, we performed the following experiment. A reference joint angle was generated by a healthy subject wearing the data glove. In this experiment, the right hand of the subject was fixed to the hand motion assist robot as shown in Fig. 7. The subject was asked to open and close the left hand and relax the right hand so as to follow the movement of the hand motion assist robot. Responses of the CM joint of the thumb are shown in Fig. 14, where (1) and (2) are joint angle responses in the abduction/adduction and flexion/extension motions, respectively. These show that the right hand driven by the motion assist robot follows the reference very well. Fig. 15 shows the force response at the third fixture in this experiment. Fig. 15 (1) and (2) are the force responses by the abduction/adduction and flexion/extension motions, respectively. These show that the force input to the human finger is not very large because the subject kept his right hand relaxed.

V. Conclusion

A newly developed hand motion assist robot with 18 DOFs has been presented. It assists not only the flexion/extension and abduction/adduction of each hand joint independently, but also the opposability of the thumb. Moreover, it assists the palmar flexion/dorsiflexion of the wrist and the pronation/ supination of the forearm so as to allow hand rehabilitation therapy in coordination with wrist motion. Experimental results have shown that the developed hand motion assist robot has good-to-excellent properties and a high potential for providing hand rehabilitation therapy by self-motion control.

To realize hand rehabilitation therapy by patients themselves, a virtual reality-enhanced display system will be added. We are planning to evaluate its recovery effect by conducting clinical tests on larger numbers of patients.

Acknowledgment

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