Development of a Hand-Assist Robot With Multi-Degrees-of-Freedom for Rehabilitation Therapy

Satoshi Ueki, *Member, IEEE*, Haruhisa Kawasaki, *Member, IEEE*, Satoshi Ito, *Member, IEEE*, Yutaka Nishimoto,
Motoyuki Abe, Takaaki Aoki, Yasuhiko Ishigure, Takeo Ojika, and Tetsuya Mouri

***Abstract*—This paper presents a virtual reality (VR)-enhanced new hand rehabilitation support system that enables patients to exercise alone. This system features a multi-degrees-of-freedom (DOF) motion assistance robot, a VR interface for patients, and a symmetrical master–slave motion assistance training strategy called "self-motion control," in which the stroke patient's healthy hand on the master side creates the assistance motion for the impaired hand on the slave side. To assist in performing the fine exercise motions needed for functional recovery of the impaired hand, the robot was constructed in an exoskeleton with 18 DOFs, to assist finger and thumb independent motions such as flexion/extension and abduction/adduction, thumb opposability, and hand–wrist coordinated motions. To enhance the effectiveness of the exercises, audio-visual instructions of each training motion using VR technology were designed with the input of clinician researchers. Experimental results from healthy subjects and patients show sufficient performance in the range of motion of the robot as well as sufficient assistance forces.**

***Index Terms*—Hand rehabilitation, master slave, self-motion control, thumb opposition, virtual reality (VR).**

I. INTRODUCTION

THE NUMBER of Japanese patients with a disability in a part of the body as a result of a cerebral vascular accident (CVA) or bone fracture is increasing concurrently with the aging of Japan's population. These patients need timely and persistent rehabilitation to recover their lost abilities and resume their normal daily activities. It is not always possible for patients to receive long-term rehabilitation training because there is a relative shortage of therapists in Japan. A solution to this problem would be a rehabilitation system that allows the patient to independently carry out rehabilitation exercises.

Compared to rehabilitation systems for lower limbs [1], [2], those for hands or fingers are relatively few. Functional electrical stimulation (FES) [3], [4] has proven to be a valuable tool in the restoration of arm function, but this approach is not suitable for self-controlled rehabilitation therapy. The reason is because FES is needed to directly input elastic signals to the body, and these signals vary among different individuals.

Many aspects of robotic arm rehabilitation therapy [5]–[7], including clinical tests [8]–[10], have been reported. Most disabilities caused by CVAs are hemiplegic, i.e., only one hand is impaired. Early rehabilitation is preferable in this case. Therefore, it is important to assist the patient in moving the impaired side of the body because it cannot be moved by the patient's own volition. Arm rehabilitation therapy with the aid of a robot [11], which involves bimanual, mirror-image, patient-controlled therapeutic exercises, is one type of self-controlled rehabilitation.

Hand rehabilitation, however, is somewhat difficult because the hand possesses many degrees of freedom (DOFs) of motion, and an attachable hand motion assist device must be small. Research thus far has been presented on the function of the fingers by FES [12], [13], hand rehabilitation devices [14]–[18], virtual reality (VR)-based stroke rehabilitation [19], and telerehabilitation [20]–[22]. However, these devices have been limited to hand motions, such as gripping and tapping, because they only assist flexion/extension of the thumb and fingers and cannot assist the abduction/adduction and thumb-opposition motions. To enhance the quality of life (QOL) of patients with hand impairment, a therapy to rehabilitate manipulation function and fine motions such as turning knobs or handling chopsticks is needed [23]. In hand rehabilitation, a robotic device is required to assist not only the flexion/extension, but also abduction/adduction motions of each joint in the fingers and thumb independently. Another major requirement for such a device is to assist the motion of thumb opposition, since the dexterous manipulation of objects by humans requires thumb opposability. Moreover, the palmar flexion/dorsiflexion of the wrist and pronation/supination of the forearm play important roles in manipulation functions and fine motions [23].

We have developed a two-finger exoskeleton device that assists the flexion/extension and abduction/adduction of the metacarpophalangeal (MP) and proximal interphalangeal (PIP) joints, and have reported a clinical test of this device involving

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S. Ueki is with Toyota National College of Technology, Aichi 471-8525, Japan (e-mail: s_ueki@toyota-ct.ac.jp).

H. Kawasaki, S. Ito, T. Ojika, and T. Mouri are with the Faculty of Engineering, Gifu University, Gifu 501-1193, Japan (e-mail: h_kawasa@gifu-u.ac.jp; satoshi@gifu-u.ac.jp; ojika.takeo@muse.ocn.ne.jp).

Y. Nishimoto is with Gifu University School of Medicine, Gifu 501-1194, Japan (e-mail: yutaka@gifu-u.ac.jp).

M. Abe is with the Department of Care and Rehabilitation, Seijoh University, Tokai 476-8588, Japan (e-mail: gifuabe@skhosp.or.jp).

T. Aoki is with the School of Medicine, Gifu University Hospital and Clinics, Gifu 501-1194, Japan (e-mail: ujimiya@gifu-u.ac.jp).

Y. Ishigure is with Marutomi Seikou Company Ltd., Seki 501-3936, Japan (e-mail: ishigure@maru-tomi.co.jp).

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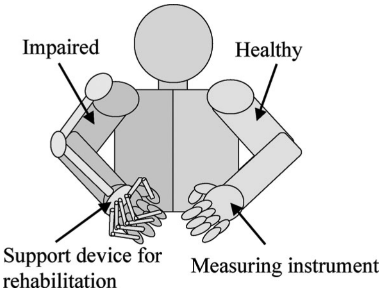


Fig. 1. Concept of self-motion control.

self-controlled rehabilitation therapy [24]. Moreover, we have developed a hand exoskeleton device that assists the joint motions of four fingers and a thumb [25]. However, this device does not adequately provide the needed thumb opposition. In order to recover the function of an impaired 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 supporting not only the flexion/extension and abduction/adduction motions of each joint in the hand, but also thumb opposability [26]. Moreover, the robot assists the palmar flexion/dorsiflexion of the wrist and pronation/supination of the forearm. To exercise more effectively, VR exercises were introduced into the system, including cooperative movements (between fingers and the wrist) and skilled movements [27]. Furthermore, a simple calibration system based on the six hand-shapes was prepared in consideration of ease-of-use. The device performance by both healthy subjects and stroke patients in the acute phase is shown.

II. HAND MOTION ASSIST ROBOT FOR REHABILITATION THERAPY

A. Self-Motion Control

Most patients who need hand rehabilitation are disabled only on one side of the body. With this in mind, we developed a self-motion-controlled hand motion assistance device [24]. The healthy hand produces the reference motions 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. 1. The self-motion control for arm motion has been presented in [11], 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.

Self-motion control will bring the following advantages to hand rehabilitation.

1) Patients can imagine training motions for their impaired hand because their opposite hand generates such motions. This ability is expected to facilitate recovery [11].
2) Since the patient directly controls the motion assist device, he or she can stop the device assistant as desired, e.g., to stop pain during the exercise.
3) The motion assistant device is unlikely to force the impaired hand to extend or flex beyond its 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 are similar in size and structure.
4) 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 [29].

A hand rehabilitation therapy called mirror therapy [30] is reported to have a restorative effect. In this therapy, a patient watches the motions of the healthy hand in a mirror and feels the impaired hand move with the normal hand. Self-motion control is expected to have an effect similar to that of mirror therapy.

B. Design Concept

During hand rehabilitation, the 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: the MP, PIP, and distal interphalangeal (DIP) joints. In light of the needs in the field of hand rehabilitation, the functions required of 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, as the PIP joint moves, the DIP joint too moves.

The thumb also has three joints: the carpometacarpal (CM), MP, and interphalangeal (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 the thumb opposition is strongly required. In addition to independent finger motion assistance, we considered the following requests in the design of the robot.

1) Coordination with wrist motion.
2) Securing the required movable range of joints and the maximum joint torque.
3) Flexibility with various hand sizes and easy attachment.
4) Safety in case of a sudden failure.

To satisfy these requirements, we have created a hand motion assist robot in the form of 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 [31] and movable joint ranges [32].

Three experienced therapists determined the joint torques necessary for normal functioning, and we measured the torques using the measurement device shown in Fig. 2. The three therapists extended and flexed a lever (which was assumed to be the patient's finger) with the maximum value of required torque five times for each joint. In that time, the point of application was changed by the representing joint. The design specifications of the hand motion assist mechanism are shown in Table I. The definition of the zero-angle position of each finger is referred to in [33].

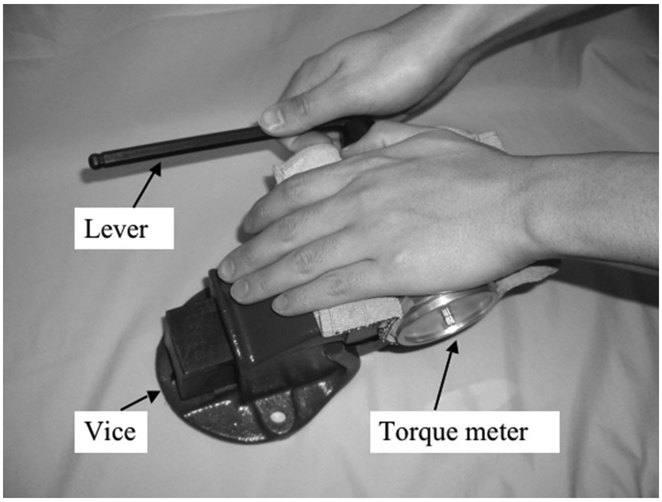


Fig. 2. Therapist's measurement of maximum joint torque.

TABLE I
DESIGN SPECIFICATIONS OF HAND MOTION ASSIST ROBOT

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

TABLE II
DESIGN SPECIFICATIONS OF WRIST MOTION ASSIST MECHANISM

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

In rehabilitation therapy, to enable the hand to manipulate objects and perform fine motions such as turning knobs and handling chopsticks, the palmar flexion/dorsiflexion motion of the wrist and pronation/supination of the forearm should be assisted in coordination with the hand motion. We call the mechanism for such assistance a wrist assist mechanism. The required joint torques of the wrist mechanism were measured in the same way as the finger joint torques. The design specifications of the wrist motion assist mechanism are shown in Table II.

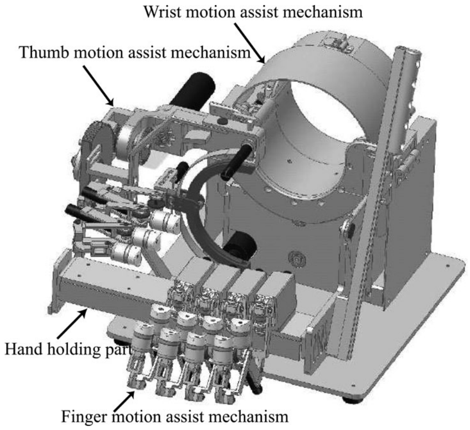


Fig. 3. Hand motion assist robot.

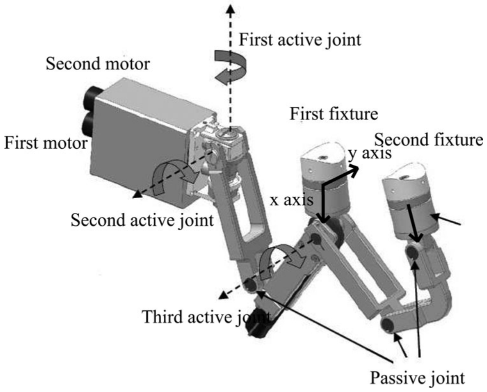


Fig. 4. Finger motion assist mechanism.

The hand motion assist robot is designed to satisfy these specifications. The hand motion assist robot that was designed is shown in Fig. 3. The details of the mechanism are explained in the following sections.

C. *Finger Motion Assist Mechanism*

A finger motion assist mechanism was constructed in the form of an exoskeleton of a finger, as shown in Fig. 4. This exoskeleton permits various finger sizes because the mechanism's active joint axes do not have to coincide with the finger joint axes 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 servomotors with rotary encoders (1.5-W dc motors, Maxon Motor, Inc.). The first and second servomotors assist the two-DOFs motions 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 a human finger, respectively, and the joint motion of that finger is independently assisted. To measure the finger joint torque, a three-axis force sensor (PD3-32-10 040, NITTA, Corp.) is mounted on each fixture. This mechanism has been described in detail elsewhere [25].

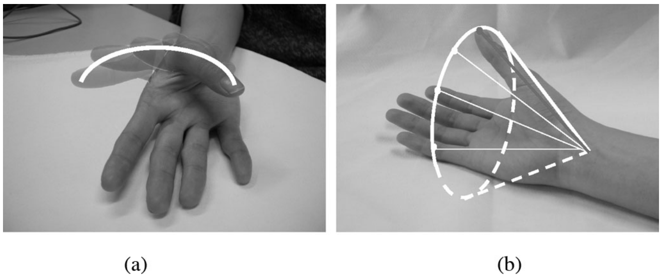
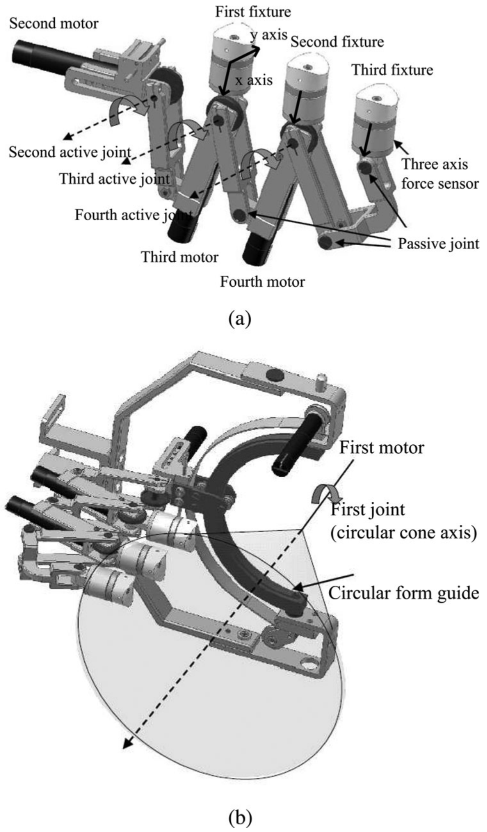

(a) (b)

Fig. 5. Opposability of the thumb: (a) Thumb opposition. (b) Circular cone motion.

D. Thumb Motion Assist Mechanism

The human thumb has IP, MP, and CM joints that generate its flexion/extension. Moreover, the CM joint generates the abduction/adduction and thumb-opposition motions simultaneously, as shown in Fig. 5(a). This thumb opposition is needed to manipulate objects dexterously, but it is difficult to assist such motion using the aforementioned finger motion assist mechanism. It can be assumed that thumb opposition is a circular cone motion, as shown in Fig. 5(b), 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. A robotic device assisting thumb opposition has never been developed.

From this point of view, a new mechanism was constructed with a functionality that enables the thumb CM joint motion approximated as a combination of the cone motions to be assisted, as shown in Fig. 6. Fig. 6(a) shows the part that assists the flexion/extension of the thumb. There are three servomotors, each with a rotary encoder, which assist the flexion/extension of the IP, MP, and CM joints independently. A 3-W dc motor was adopted for the CM joint. 1.5-W dc motors were adopted for the other finger joints. 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 three-axis force sensor is mounted on each fixture. Fig. 6(b) shows the part that generates a circular cone motion to assist with thumb opposition. We adopted a circular form guide because the tip of the cone is located in the human wrist. The first servomotor drives the flexion/extension assist mechanism on the surface of the circular cone to make a circular cone motion and thereby assist thumb opposition.



(a)

(b)

Fig. 6. Thumb motion assist mechanism: (a) motion assist part of extension and flexion and (b) motion assist part for thumb opposition.

E. Hand-Holding Part

In our mechanical design, the average sizes of fingers and thumbs were based on statistical data about Japanese hands [31]. However, it is necessary for the hand motion assist robot to be applicable to various hand sizes. To accommodate different finger sizes, the positions of the finger and thumb motion assist mechanisms can be shifted not only anteroposteriorly, but also heightwise on the hand-holding part. The adjustment ranges are 32 mm anteroposteriorly and 20 mm heightwise. This permits most Japanese adults to use the hand motion assist robot.

F. Wrist Motion Assist Mechanism

The human wrist exhibits three different motions: palmer flexion/dorsiflexion; pronation/supination; and abduction/adduction. In an actual hand rehabilitation therapy, the first two motions are especially weighted because of frequent usage in daily life: tapping a computer keyboard or pushing button switches requires palmar flexion/dorsiflexion, while turning a door knob requires pronation/supination of the wrist. However, abduction/adduction is only needed for several activities, such as playing the guitar. Therefore, the hand motion assist robot was designed to assist only these two wrist motions: flexion/dorsiflexion and pronation/supination. The structure of the wrist motion assist mechanism is illustrated in Fig. 7, in which the first and second joints correspond with the pronation/supination and palmar flexion/dorsiflexion motions, respectively. The two joint axes are orthogonal to each other, and each actuator is a servomotor with a rotary encoder (7-W dc motors, Maxon Motor, Inc.). 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 II, in which numerical

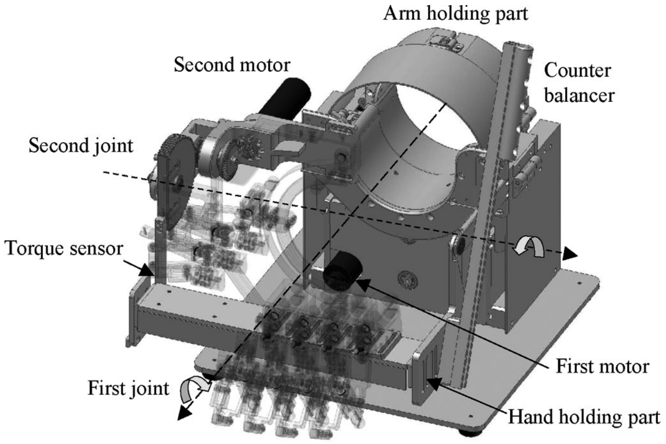


Fig. 7. Wrist motion assist mechanism.

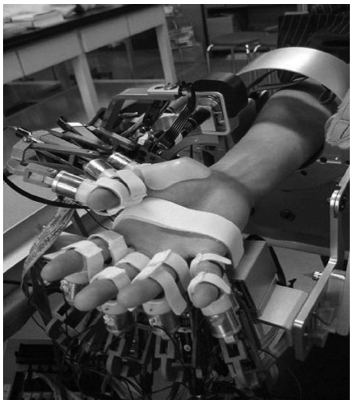


Fig. 8. Human hand fixed in the hand motion assist robot.

values are obtained in the same way as those for the finger motion assist mechanism.

G. Fixing the Hand and Arm to the Robot

The patient's forearm and hand are attached to the hand motion assist robot, as shown in Fig. 8. In this method, the patient's impaired hand is directly fixed to the robot by a band. Although this method takes some attaching/detaching time, it can generate the required joint torque because it fixes the hand tightly. The forearm is attached with a cuff and is fixed by an arm-holding part. Various arm sizes can be accommodated by modifying the air pressure of the cuff. Although the patient needs help in getting their hand into the device, he or she can then exercise alone. They can thus receive long-term rehabilitation training.

III. CONTROL SYSTEM

In order to realize the self-motion control strategy, four controllers are prepared: a personal computer for measuring unaffected hand motion; a controller for the motion assistance mechanisms of the fingers; one of the impaired wrist; and the safety supervisor. The structure of the control system is illustrated in Fig. 9.

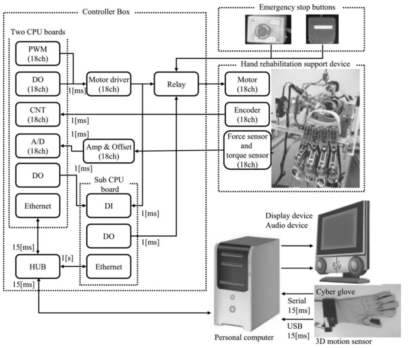


Fig. 9. Control system structure.

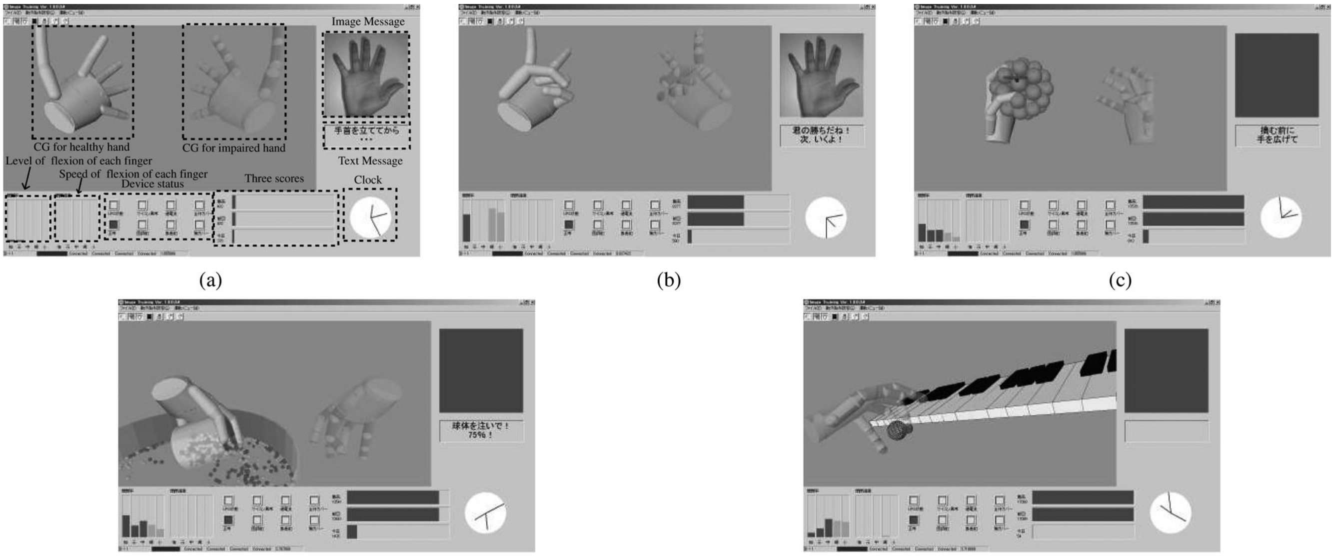
A. VR System

A Cyber Glove (Virtual Technologies Co.) and a "3-D motion sensor" are connected to a personal computer that provides VR environments. The Cyber Glove attached to the normal hand measures the finger joint angles, while the 3-D motion sensor on the glove measures the postural angle of the hand. The data on the finger joint angles are used to calculate the reference angles of the hand rehabilitation device. The sampling time of both devices is 15 ms, the resolution of the Cyber Glove is 0.5°, and the resolution of the 3-D motion sensor is 1.0°. When the patient attaches his or her impaired hand to the device, the link mechanisms construct a closed loop with the finger because of the device's exoskeletal structure. In the closed loop, there are two passive joints and one active joint, all three of which are driven by a single dc motor. Based on the kinematic relation of the closed-loop structure, the reference angles of the active joint in the motion assistance mechanism are determined solely by solving the inverse kinematic problems [25]. These reference angles bring the impaired hand into symmetry with the normal hand by means of the motion assistance of the device. The reference data are transferred every 15 ms.

The personal computer provides the user with a graphical user interface (GUI). The user can command the device's controller using this interface. The joint angle data are used to draw the impaired hand's posture using computer graphics by OpenGL. The GUI provides a function with which to improve the system's performance. That function is explained in Section IV.

B. Control Equipment

The device uses an "HRP-3P-CN" controller board with an I/O module for a multichannel link node (General Robotics, Inc.) to control the joint angles of the exoskeleton link in relation to the reference position. The control process, joint angle detection, force information measurement, control law computation, and pulse width modulation output are performed in that order. Proportional position control is adopted as a control law. A series of these processes is executed as a real-time process in 1 ms. The force information will be used to limit the output torque. In order to utilize the multi-DOFs hand rehabilitation device safely and efficiently, we prepared several control modes. Details of this controller appear elsewhere [28].



手首を立ててから
・・・

君の勝ちだね！
次、いくよ！

掴む前に
手を広げて

球体を注いで！
75%！

(a) (b) (c) (d) (e)

Fig. 10. Virtual reality system. (a) Measurement of movable range. (b) Rock-paper-scissors. (c) Pinching (or grasping) fruit. (d) Pouring movement. (e) Piano sounds generated by tapping a ball.

C. Safety Features

The following safety features have been adopted.

1) *Two emergency stop buttons:* One for the therapist, the other for the patient as a foot push-button. If either button is pushed, the power supply to the motor driver is cut off and the robot stops.
2) The status of all joint angles and joint torques is also periodically monitored (the sampling frequency is 1000 Hz). If the joint torques are over a prescribed limit, the controller stops the robot.
3) *Status supervision and output-limiting facility of the motor driver:* The output is limited by a current-limiting circuit, and the safety supervisor keeps watch on it periodically. If the status is abnormal, the safety supervisor cuts off power to the motor driver.
4) These three controllers each send a signal to the safety supervisor every second in order to confirm the normal operation of the program. The safety supervisor determines that there is an obstacle in the controller when at least one of the controllers stops emitting a signal. The safety supervisor observes the electric current of the dc motor as well as the emergency stop buttons.

This system was designed as a fail safe system.

IV. VR EXERCISES

To exercise more effectively in order to perform activities of daily living (ADL), it is necessary to rehabilitate cooperative and skilled movements of the impaired finger. The exercises must include not only each movement of the impaired fingers, but also cooperative and skilled movements. Furthermore, the exercises must be created with self-motion control taken into account. With this in mind, four therapeutic exercises (*Rock-paper-scissors*, *pinching (or grasping) fruit*, *pouring movement*, *and generation of piano sounds by tapping a ball*) were created based on the advice of clinician researchers. Moreover, *measurement of movable range* was added for the evaluation of rehabilitation and the determination of exercise level. As can be seen in Fig. 10, all of the exercises have a similar GUI. Each exercise is voice guided and features scoring of reactions, monitoring of states, and recording of motion data. The voice-guided system helps the patient understand and perform the exercises and gives encouragement. Also, the GUI shows the same text message when the patient does not understand the verbal instructions. The game element is taken into consideration by scoring the patient's reactions, e.g., task completion time or joint angles. These scores are recorded and the GUI shows the three scores (today, best, and last time) by status bars. Moreover, the scores from the past several days, including the patient's best scores, are displayed at the end of the exercise, as shown in Fig. 11. These functions are expected to enhance the patient's motivation and thus promote rehabilitation. The joint angles, their velocity, and force are recorded and used to evaluate the recovery condition. The level of flexion of each finger is shown by status bars on the GUI. Also, the GUI shows the device status (to show whether the device is malfunctioning) by eight tetragons, and the clock on the GUI has three hands (second hand, exercise hand, and training hand). The exercise hand rotates 360° with a period of predetermined time, and the training hand rotates 360° with a period of 20 min. The length of one period of rehabilitation training in Japan is 20 min.

Measurement of movable range determines the patient's state and exercise level. Therefore, the *measurement of movable range* measures the movable range first. The exercise level is prepared in three stages. For example, in *rock-paper-scissors*, the judgment criterion is changed depending on the movable range. The patient sequentially tries the following movements under voice guidance and while observing the display images: 1) clasping the hands, 2) unclenching the hands, 3) procurvation/

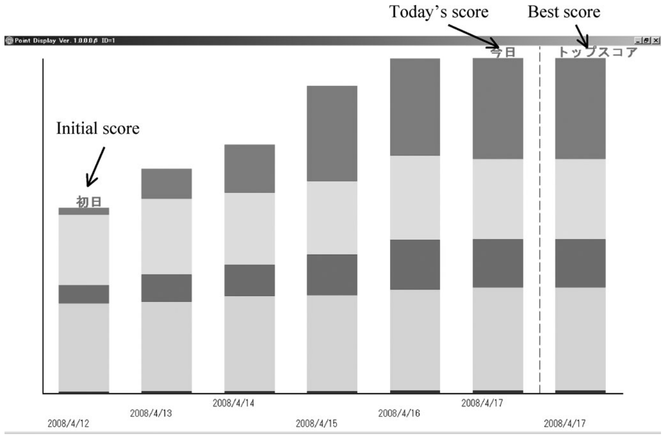


Fig. 11. Screen showing displayed scores.

dorsiflexion of the wrist, and 4) formation of a scissoring motion.

Rock-paper-scissors is not an ADL, but it consists of the following movements. Making the *paper-rock* motion requires the synchronous flexion/extension movement of the fingers. This movement is essential for carrying an object. Moreover, a synergy [34] appears when recovering from the acute phase that almost never moves. Even when the patient only wants to move one finger, other fingers are moved with it, i.e., the middle, ring, and pinky fingers also move when the patient moves the index finger. This is called "synergy," which emerges in the beginning of recovery. Since forming a *scissor* with the hand is a composite motion of the extension of the index and middle fingers combined with flexion of the others, we can expect the effects of separation and independence from synergy (a synergy is considered a problem with recovery of the nerve).

Pinching (or grasping) fruit simulation exercises the thumb and the fingers. It is well known that the human hand has a unique configuration, called *fingers-thumb opposability*. The grasping or pinching exercise encourages the recovery of thumb-opposition motion and prevents contracture. The pinching motion requires not only precise control of the thumb, but also the cooperative movement of the thumb and index (and middle) finger. This movement is indispensable to rehabilitation toward ADL. Also, as the patient's ability to pinch or grasp improves, the size of the fruit gradually becomes smaller (or larger).

Pouring movement is modeled after the fundamental exercises. By pronation/supination of the forearm, the patient pours small balls from one cup into another. This requires a grasping motion and pronation/supination of the forearm. In particular, the pronation/supination of the forearm is indispensable as it is necessary to turn a doorknob, turn a key in a lock, scoop things up with a spoon, and so on.

Generation of piano sounds by tapping a ball is an exercise to develop the independence of each finger. The patient taps a colored ball, which is shown and hidden rhythmically, using an assigned finger in order to generate a piano tone. The independent motion of each finger is a useful motion to have, as it enables such actions as operating a keyboard. Regaining this motion will be helpful for social reintegration.

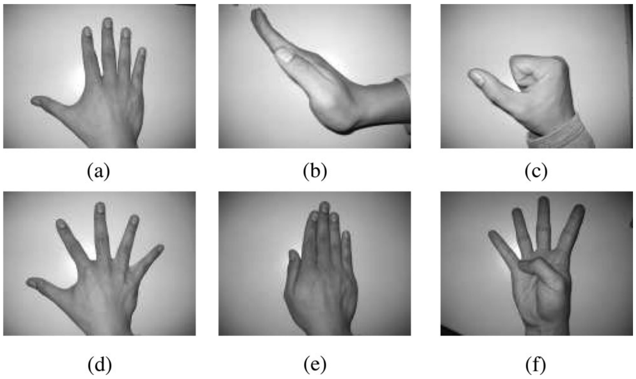


Fig. 12. Handshapes in calibration system. (a) Natural situation. (b) Dorsiflexion of 45 degrees. (c) Flexion of MP and PIP joints of fingers. (d) Opened adduction/abduction of MP joint of fingers and adduction/abduction of CM joint of thumb. (e) Closed adduction/abduction of MP joint of fingers and adduction/abduction of CM joint of thumb. (f) Flexion of the thumb toward fifth metacarpal head.

A. *Simple Calibration System for the Cyber Glove*

The joint angles of the hand were calculated from 16 raw values of the Cyber Glove. However, if the user's hand size does not match the glove's size, an accurate joint angle cannot be obtained. Therefore, self-motion control and VR exercises require the calibration of the glove. Moreover, patients and therapists do not have the technical skill of an electric machine. With this in mind, we prepared a simple calibration system based on the six handshapes shown in Fig. 12. With the handshapes in Fig. 12, the therapist clicks on a button displayed by the GUI. We wanted the handshapes to have the following qualities.

1) *Easy comprehensibility:* The patient can easily make the shapes, and the shapes are similar to those made in ADL.
2) *Quick:* The shape can be made in a single, quick motion.
3) *Low-impact:* Making the shape does not cause pain.

Moreover, we considered the sensor position and accurateness for each of the six handshapes. In this calibration method, the time required is less than 4 min, and there is no need for any other device to be used. This calibration method led to good results except for the thumb of a hand that was too small (in the tests, the hand was 179.8-mm long and 79.7-mm wide).

V. EVALUATION OF DEVICE PERFORMANCE

A. *Assistance Force Evaluation*

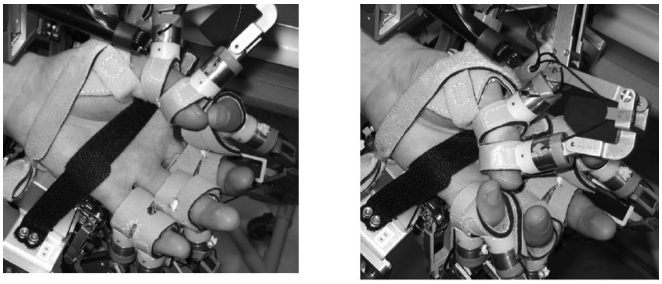
The torque of the developed robot was measured to evaluate whether the design specifications were satisfied. The output force was measured three times using a force gauge, and the torque was calculated using the distance between the joint position and point of application. The results are shown in Table III. Also, the specifications of movable range were satisfied. Therefore, the developed robot satisfied the design specifications.

B. *Assist Motion of the Thumb Opposition*

The assist motion of the thumb opposition is an important function for hand rehabilitation support. Fig. 13 shows the assist motion for the thumb opposition. Fig. 13(a) shows the

TABLE III
MAXIMUM JOINT TORQUE

Finger	MP	Extension/Flexion	0.51 (Nm)
		Adduction/Abduction	0.79 (Nm)
	PIP	Extension/Flexion	1.66 (Nm)
Thumb	CM	Extension/Flexion	1.80 (Nm)
		Adduction/Abduction	3.72 (Nm)
	MP	Extension/Flexion	1.21 (Nm)
	IP	Extension/Flexion	1.58 (Nm)
Wrist		Pronation/Supination	15.7 (Nm)
		Palmar Flexion/Dorsiflexion	4.4 (Nm)



(a) (b)

Fig. 13. Assist motion of the thumb opposition. (a) Index finger. (b) Pinky finger.

thumb-opposition motion for the index finger, and Fig. 13(b) shows the thumb-opposition motion for the pinky finger. Thus, the proposed system can support thumb opposability.

C. Frequency Characteristics

The frequency characteristics of the PD control were measured to evaluate the responsiveness of the hand motion assist robot. To measure the frequency characteristics as a linear system, the amplitude of the sinus signal was 1°. Fig. 14 shows the frequency characteristics of the finger motion assist mechanism: (a) is the abduction/adduction of the MP joint; (b) is the flexion/extension of the MP joint; and (c) 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 with flexible finger joints was attached to the hand motion assist robot to maintain a closed loop and avoid free motion by a passive joint. The bandwidths of Fig. 14(a)–(c) were about 2.5, 5.0, and 2.5 Hz, respectively. Fig. 15 shows the frequency characteristics of the thumb motion assist mechanism: (a) is the abduction/adduction of the CM joint; (b) is the flexion/extension of the CM joint; and (c) is the flexion/extension of the MP joint. The bandwidths of Fig. 15(a)–(c) are about 7.0, 4.0, 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.

D. Experiment of Self-Motion Control

Six healthy subjects and six stroke patients in the acute phase were asked to use this rehabilitation system to evaluate the performance of the developed robot. The measured data are: joint angles of the installed motor and the force at the force sensors. The actual flexion angles were calculated from these data based on the forward kinematics. The results for one healthy subject and one stroke patient, which were typical results, are shown in Fig. 16. The healthy 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 because the targets are limited to the stroke patient in the acute phase. Fig. 16(a), (c), (e), (g), (i), (k), and (m) were by the healthy subject, while Fig. 16(b), (d),

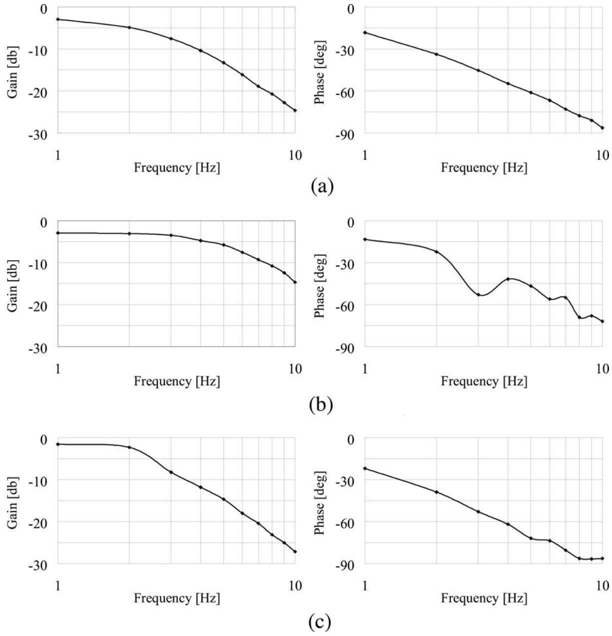


Fig. 14. Frequency characteristics of the finger motion assist mechanism. (a) Abduction/adduction of MP joint. (b) Flexion/extension of MP joint. (c) Flexion/extension of PIP joint.

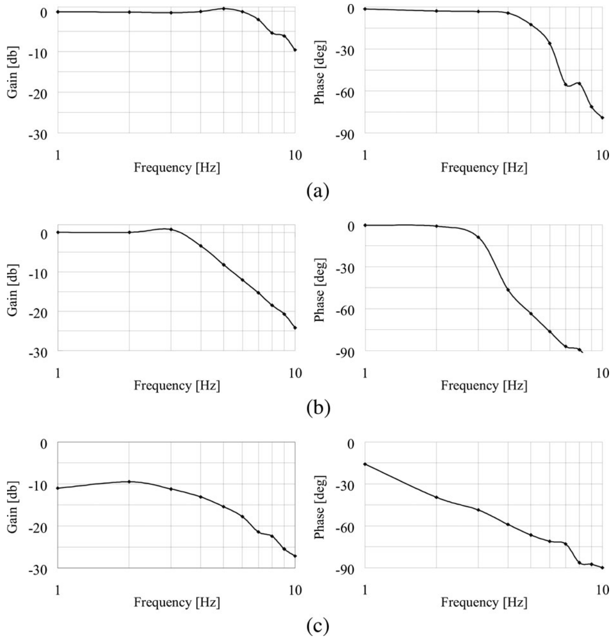


Fig. 15. Frequency characteristics of the thumb motion assist mechanism. (a) Abduction/adduction of CM joint. (b) Flexion/extension of CM joint. (c) Flexion/extension of MP joint.

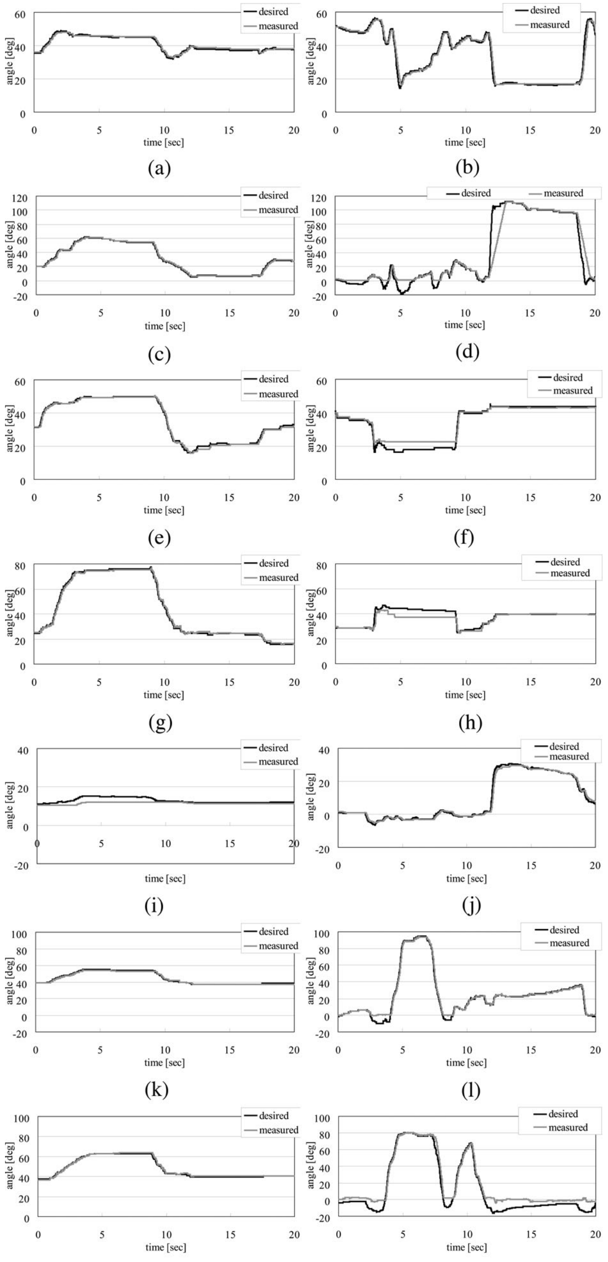


Fig. 16. Joint angle responses by patient self-motion control: (a), (c), (e), (g), (i), (k), (m) were by the healthy subject, (b), (d), (f), (h), (j), (l), (n) were by the patient. (a) and (b) Abduction/adduction of CM thumb joint, (c) and (d) flexion/extension of CM thumb joint, (e) and (f) flexion/extension of MP thumb joint, (g) and (h) flexion/extension of IP thumb joint, (i) and (j) abduction/adduction of MP index joint, (k) and (l) flexion/extension of MP index joint, and (m) and (n) flexion/extension of PIP index joint.

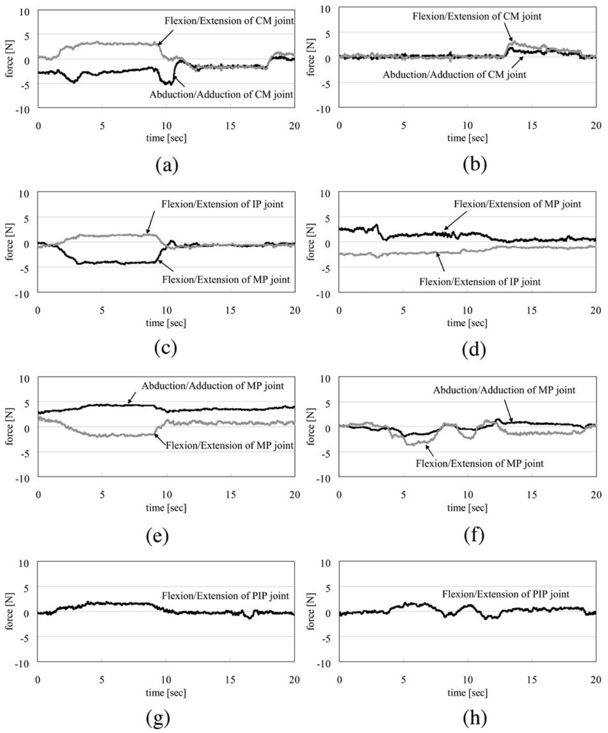


Fig. 17. Force responses by the self-motion control: (a), (c), (e), (g) were by the healthy subject and; (b), (d), (f), (h) were by the patient. The elements of abduction/adduction of CM thumb joint are *x* element of force sensor in (a) and (b), the elements of flexion/extension of CM thumb joint are *y* element of force sensor in (a) and (b), the elements of flexion/extension of MP thumb joint are *y* element of force sensor in (c) and (d), the elements of flexion/extension of IP thumb joint are *y* element of force sensor in (c) and (d), the elements of abduction/adduction of MP index joint are *x* element of force sensor in (e) and (f), the elements of flexion/extension of MP index joint are *y* element of force sensor in (e) and (f), the elements of flexion/extension of PIP index joint are *y* element of force sensor in (g) and (h).

(f), (h), (j), (l), and (n)were by the patient. Fig. 16(a) and (b) shows the abduction/adduction of CM thumb joint, Fig. 16(c) and (d) the flexion/extension of CM thumb joint, Fig. 16(e) and (f) the flexion/extension of MP thumb joint, Fig. 16(g) and (h) the flexion/extension of IP thumb joint, Fig. 16(i) and (j) the abduction/adduction of MP index joint, Fig. 16(k) and (l) the flexion/extension of MP index joint, and Fig. 16(m) and (n) the flexion/extension of the PIP index joint. These show that the right hand driven by the motion assist robot follows the reference well. However, a trajectory error is observed when the reference angle varies rapidly because of the limitation of the joint torque. Fig. 17 shows the force response at the third fixture in this experiment. Fig. 17(a) and (b) shows the force responses by the abduction/adduction and flexion/extension motions of the CM thumb joint, Fig. 17(c) and (d) the force responses by the flexion/extension motions of the MP and IP thumb joint, Fig. 17(e) and (f) the force responses by the abduction/adduction and flexion/extension motions of the MP index joint, and Fig. 17(g) and (h) the force responses by the flexion/extension motions of the PIP index joint. The force responses by the abduction/adduction motion of Fig. 17(a), (b), (e), and (f) are the *x* element of each force sensor. The others are the *y* element of each force sensor (each axis is shown in Figs. 4 and 6). These show that the force input to the human finger is not very large because the subject kept his right hand relaxed.

VI. CONCLUSION

A VR-enhanced hand rehabilitation support system with a symmetric master–slave motion assistant has been presented for use in self-performing rehabilitation therapies. In this system, an impaired hand's individual finger joint motions are supported by an exoskeleton device controlled by the finger joint motion of the patient's healthy hand. The device assists not only the flexion/extension and abduction/adduction of each joint in the hand 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. To exercise more effectively in preparation to resume ADL, a VR environment displaying an effective exercise program was created. The response of the motion assist mechanism showed that this hand motion assist robot has good-to-excellent properties and a high potential for providing hand rehabilitation therapy by self-motion control.

In the future work, we will improve the quality of the system and evaluate the recovery effect with many clinical evidences.

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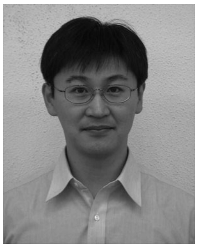
Satoshi Ueki (M'08) received the M.S. and Dr. degrees in mechanical engineering from Gifu University, Gifu, Japan, in 2004 and 2007, respectively.

From April 2007 to March 2010, he was a Postdoctoral Researcher in the Virtual Systems Laboratory, Gifu University. He is currently an Assistant Professor at Toyota National College of Technology, Aichi, Japan. His research interests include robotics, systems engineering, and cybernetics.

Haruhisa Kawasaki (M'91) received the M.S. and Dr. degrees from Nagoya University, Nagoya, Japan, in 1974 and 1986, respectively.

He is currently a Professor with the Faculty of Engineering and the Deputy Director of Gifu University Young Researchers Education Center for Innovation, Gifu University, Gifu, Japan. From 1974 to 1990, he was a Research Engineer at NTT laboratories. From 1990 to 1994, he was a Professor at Kanazawa Institute of Technology, Japan. From July 1998 to January 1999, he was a Visiting Professor at the University of Surrey, Surrey, U.K. His research interests include robot control, humanoid robot hands, haptic interface in virtual reality, and computer algebra of robotics.

He is a member of many organizations, such as the Japan Society of Mechanical Engineers (JSME), the Robotics Society of Japan (RSJ), the Society of Instrument and Control Engineers, and the Virtual Reality Society of Japan. He is a Fellow of JSME and RSJ. He has received several awards, including the Best Paper Award of the World Automation Congress 2004, Prizes for Science and Technology, Ministry Award from MEXT-JAPAN in 2006, JSME Funai Award in 2009, and the 18th Industry-Academia-Government Collaboration Promotion Award, Ministry Award from MIC-JAPAN in 2010. He was the National Organizing Committee Chair of the 9th International Federation of Automatic Control Symposium on Robot Control (2009).



Satoshi Ito (M'94) was born in Japan in 1968. He received the B.S., M.S. and Dr. degrees from Nagoya University, Nagoya, Japan, in 1991, 1993, and 1999, respectively.

From 1994 to 1996, he was a member of the technical staff in the Laboratory for Bio-Mimetic Control Systems, Bio-Mimetic Control Research Center, where he was a Research Scientist from 1997 to 1999. Since 1999, he has been a Research Associate with the Faculty of Engineering, Gifu University, Gifu, Japan, where he is currently an Associate Professor. His research interests include robotics, systems engineering, and cybernetics.

Yutaka Nishimoto was born in Tokushima, Japan, in 1956. He received the M.D. and the Ph.D. degrees from Gifu University, Gifu, Japan, in 1981 and 1986, respectively.

From 1986 to 1988, he was a Staff Member in the Department of Orthopaedics, Prefectural Gifu Hospital. From 1988 to 2002, he was an Assistant Professor in the Department of Orthopaedics, Gifu University Hospital. From 2002 to 2005, he was an Associate Professor in the Department of Medical Surgical Nursing, Gifu University. Since 2005, he has been a Professor in the Department of Medical Surgical Nursing, Gifu University School of Medicine. He has been engaged in the treatment of bone and soft tissue tumors, especially disabled limbs after treatment of the tumors.

Dr. Nishimoto is a member of the Japanese Orthopaedic Association, the Japanese Society of Clinical Oncology, the Japanese Association of Rehabilitation Medicine, the Japan Academy of Nursing Science, the Japan Ergonomics Society, the Society of Instrument and Control Engineers, etc. He has been a Councilor of the Central Japan Association of Orthopaedic Surgery and Traumatology since 1997.

Motoyuki Abe was born in 1955. He received the M.D. degree from the University of Occupational and Environmental Health, Kitakyushu, Japan, and the Ph.D. degree from Saitama Medical University, Saitama, Japan.

Since 2007, he has been a Professor in the Department of Care and Rehabilitation, Seijoh University, Aichi, Japan. His research interests include robotic rehabilitation of stroke patients and the study of musculoskeletal and vascular ultrasound.

Prof. Abe is a member of the Japanese Association of Rehabilitation Medicine, the Japanese Orthopaedic Association, the Japan Stroke Society, and the Japanese College of Angiology.

Takaaki Aoki was born in 1962. He received the M.D. and Ph.D. degrees in 1991 and 1996, respectively, from Gifu University, Gifu, Japan.

He has studied and researched the biomechanics of osteotomy of the knee at the University of Iowa. He is currently the Director of the Department of Rehabilitation (Orthopaedic Surgery), Gifu University Hospital and Clinics, Gifu.

Dr. Aoki is a member of councilors in the Japanese Association of Rehabilitation Medicine and *Bulletin of the Japanese Society of Prosthetics Orthotics*.

Yasuhiko Ishigure was born in Gifu, Japan, in 1968.

Since 1999, he has been with Marutomi Seiko Company Ltd., Seki, Japan, where he is actively engaged in research and development on rehabilitation support systems, multifingered haptic interface, and pruning robots.

Dr. Ishigure is a member of the Robotics Society of Japan.

Takeo Ojika was born in 1939. He received the B.S. degree in engineering from Waseda University, Tokyo, Japan, the M.S. and Dr. Phil. degrees from the Graduate School of Engineering, Kyoto University, Kyoto, Japan, in 1970 and 1975, respectively, and the Dr. Sci. degree for research of numerical analysis of multipoint boundary value problems from Kyoto University, Kyoto, Japan.

From 1962 to 1967, he was an Engineer with Mitsubishi Heavy Industry Ltd. From 1972 to 1988, he was an Associate Professor at Osaka Kyoiku University. From 1988 to 2002, he was a Professor with the Faculty of Engineering, Gifu University, Gifu, Japan, where he was engaged in research on virtual reality (VR) and its application to culture heritages, and medical supporting and education systems, and established the Virtual System Laboratory. He is currently a Professor Emeritus of this university. He contributed to establish the International Society on Virtual Systems and MultiMedia (VSMM, www.vsmm.org) in 1995 and then organized its international conferences in many countries.

Dr. Ojika is the Honorary President of the International Society on VSMM.

Tetsuya Mouri received the M.S. and Dr. degrees in mechanical engineering from Nagoya Institute of Technology, Nagoya, Japan, in 1997 and 2000, respectively.

He is currently an Associate Professor with the Faculty of Engineering, Gifu University, Gifu, Japan. His research interests include the areas of humanoid robot hands, haptic interface in virtual reality, and identification of contact conditions.