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Development of Virtual Reality Exercise of Hand Motion Assist Robot for Rehabilitation Therapy by Patient Self-Motion Control

Satoshi UEKI, Yutaka NISHIMOTO, Motoyuki ABE, Haruhisa KAWASAKI,
Satoshi ITO, Yasuhiko ISHIGURE, Jun MIZUMOTO, and Takeo OJIKA.

Abstract— **This paper presents a virtual reality-enhanced hand rehabilitation support system with a symmetric master-slave motion assistant for independent rehabilitation therapies. Our aim is to provide fine motion exercise for a hand and fingers, which allows the impaired hand of a patient to be driven by his or her healthy hand on the opposite side. Since most disabilities caused by cerebral vascular accidents or bone fractures are hemiplegic, we adopted a symmetric master-slave motion assistant system in which the impaired hand is driven by the healthy hand on the opposite side. A VR environment displaying an effective exercise was created in consideration of system's characteristic. To verify the effectiveness of this system, a clinical test was executed by applying to six patients.**

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.

The 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 [1], [2], hand rehabilitation devices [3], [4], [5], [6], virtual reality-based stroke rehabilitation [7], and tele-rehabilitation [8], [9], [10], have been presented. However, 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 (QOL) of patients with hand impairments, a rehabilitation therapy for manipulation function and fine motions such as turning knobs or handling chopsticks is needed [11]. 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[11].

We have developed a hand rehabilitation device that has 18 DoFs of motion: 4 DoFs for the thumb motion assistance mechanism, 3 DoFs for each finger motion assistance mechanism, and 2 DoFs for the wrist joint[12], [13], as shown in Fig. 1(a). Virtual reality exercises should include cooperative movements (between a finger and another, or between the finger and the wrist) and skilled movements. In this paper, concepts of the virtual reality-enhanced hand rehabilitation support system and the evaluation results of the patient's comments are presented.

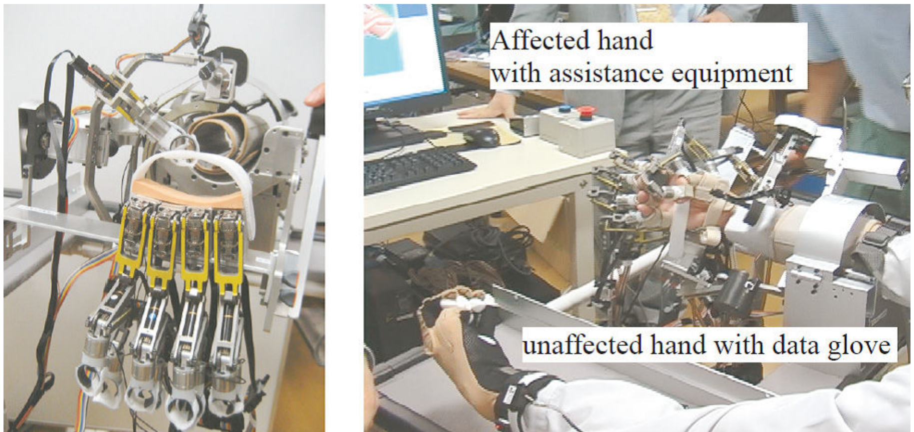
II. HAND MOTION ASSIST ROBOT FOR REHABILITATION THERAPY

The subject of the developed system is hemiplegic's patient who is caused by CVA. Such a patient has a cranial nerve problem, and one side of the hands is hemiplegic, but the other is normal in general. Rehabilitation is distinguished by the acute phase, the recovery period, and the maintenance period according to time from the appearance of disease. The rehabilitation therapy is important in the acute phase and the recovery period for recovery from hemiplegic.

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[14]. The healthy 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.The self-motion control will bring the following advantages to the hand rehabilitation: (1) 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

Satoshi Ueki is with Faculty of Engineering Gifu University, Yanagido 1-1, Gifu, Japan s_ueki@gifu-u.ac.jp
Yutaka Nishimoto is with Gifu University School of Medicine, Yanagido 1-1, Gifu 501-1194, Japan yutaka@gifu-u.ac.jp
Motoyuki Abe is with the Gifu Central Hospital, 3-25 Kawabe, Gifu 501-1198, Japan gifuabe@skhosp.or.jp
Haruhisa Kawasaki is with Faculty of Engineering, Gifu University, Yanagido 1-1, Gifu 501-1193, Japan h_kawasa@gifu-u.ac.jp
Satoshi Ito is with Faculty of Engineering, Gifu University, Yanagido 1-1, Gifu 501-1193, Japan satoshi@gifu-u.ac.jp
Yasuhiko Ishigure is with Marutomi Seikou Co., Ltd, 3147-7 aza ikuda, kurachi, Seki, 501-3936 Japan ishigure@maru-tomi.co.jp
Jun Mizumoto is with Marutomi Seikou Co., Ltd, 3147-7 aza ikuda, kurachi, Seki, 501-3936 Japan mizumoto@maru-tomi.co.jp
Takeo Ojika is with Marutomi Seikou Co., Ltd, 3147-7 aza ikuda, kurachi, Seki, 501-3936 Japan ojika.takeo@muse.ocn.ne.jp



(a) Overview. (b) Operation by a self-motion control.

Fig. 1. A hand rehabilitation equipment with 18 DoFs.

the disabled function[15]. (2) 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. (3) 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. (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 [16]. It is reported that a hand rehabilitation therapy called mirror therapy [17] 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. This operation achieved by using self-motion control is shown in Fig. 1(b).

B. *Structure of control system* (Fig. 2)

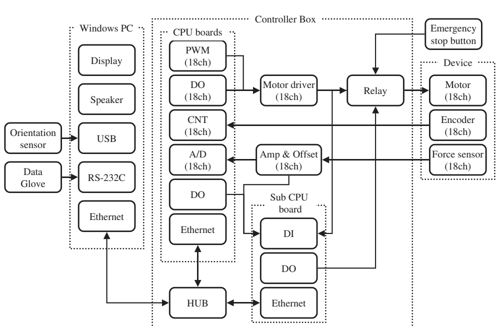


Fig. 2. Structure of control system

1) A personal computer: A personal computer (PC) is connected with a "cyber glove" (Virtual Technologies Co.) attached to the normal hand side that can measure the finger joint angles and the "3D motion sensor" on the glove that can measure the posture of the hand. The data of the finger joint angles are used to calculate the reference angles of the hand rehabilitation device. 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 exoskeltal structure. In the closed loop, there are two passive joints and one active joint driven by the 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 solely determined by solving the inverse kinematic problems[13]. These reference angles bring the impaired hand into symmetry with the normal hand by means of the motion assistance of the device.

The PC provides the users a graphical user interface(GUI). Through this interface the users can give commands to the device's controller. The joint angle data are used to draw the impaired hand's posture using computer graphics by OpenGL. The GUI provides function for performance improvement of the system. The function will be explained in next section.

2) Controller of the hand rehabilitation device: A "HRP-3P-CN" controller board with an I/O module for multi-channel link node (General Robotics Inc.) is used as the device's controller that controls the joint angles of the exoskeletol link in relation to the reference position. In the control process, joint angle detection, force information measurement, control law computation, and PWM output are performed in this 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.

3) The safety supervisor: The above three controllers send a signal to the safety supervisor every 1[s] in order to notify the normal operation of the program. The safety supervisor determines to be an obstacle in the controller when receiving no signal from each controller. The safety supervisor observes the electric current of the DC motor as well as the emergency stop bottoms.

III. Virtual Reality Exercises

For the activities of daily living (ADL), the rehabilitation for cooperative and skilled movements of the impaired finger is necessary. The exercises must include not only each movement of fingers but also cooperative movements and skilled movement. Furthermore, the exercises must be created in consideration of self-motion control. With that in mind, four therapeutic exercises (*Scissors-paper-rock*,*Pinching (or grasping) fruit*,*Pouring movement*,*Generation of piano sounds by tapping a ball*) were created based on the advice provided by the clinician researchers. Moreover, the measurement of movable range is added for the evaluation of rehabilitation and the determination of exercise level. As can be seen in Fig. 3, all exercises have a similar GUI. As the common function of it, a voice guide system, scoring of reactions, monitoring of states, and recording motion data are provided. The function of the voice guide system offers guidance for exercises and gives encouragement to the patient. The game element is taken into consideration by scoring the patient's reactions. These scores are recorded, and displayed on a monitor. It is expected that these functions enhance the motivation of the patient for rehabilitation. The monitor of states is to display the range and its velocity when opening/closing the impaired hand. The joint angles, its velocity, values of the force sensor are recorded, and these are used to evaluate the recovery condition.

Measurement of movable range purposes to measure patient's state and determination of exercise level. Therefore, it will be given at the first. The exercise level prepared three stages. For example, in the *Scissors-paper-rock*, judgement criterion is changed depending on movable range. The patient sequentially tries the following movements under the voice guides and the displayed CGs: 1) clasping the hand, 2) unclenching one's hands, 3) the procurvation/dorsiflexion of the wrist, and 4) the formation of a scissor.

Scissors-paper-rock is not ADL, but there are the following meanings. The realization of *paper-rock* needs the synchronous flexion/extension movement of the fingers. This movement is essential for the grasping motion, and its realization enables to carry an object. Moreover, a synergy appears when recovering from the acute phase that almost never moves. Since making the formation of a *scissor* is a composite motion by extension of index and middle fingers, and flexion of the others, we can expect an effect of separation and independence from synergy(a synergy is considered to be a problem of recovery of the nerve).

Pinching (or grasping) fruit simulation exercises the thumb and other fingers. It is well known that the human hands have a unique configuration, called *fingers-thumb opposability*. The exercises of grasping or pinching encourages the recovery of the thumb opposition motion and prevent the contracture. The realization of pinching needs not only precise control of thumb but also the cooperative movement of thumb and index (and middle). This movement is one of indispensable motions for the rehabilitation towards ADL. Also, when pinching or grasping succeeded, the size of the fruit gradually becomes small (or large).

Pouring movement is modeled after the fundamental exercises. By pronation/supination of the forearm, small balls in a cup are poured to another lower cup. The movement includes the grasping motion and pronation/supination of the forearm. In particular, the pronation/supination of the forearm is indispensable motions, which are necessary for the rotation of the doorknob, the opening and shutting of the key, scooping up with a spoon, and so on.

Generation of piano sounds by tapping a ball is an exercise for the independence of each finger. The patient hits a colored ball, which is shown/hidden rhythmically, by its assigned finger and if succeeded well, then its corresponding piano sound is generated. The skilled movement, like a rhythmical motion of independence of each finger, greatly expands the way of the rehabilitation into society.

IV. CLINICAL TRIALS BY PATIENTS

The clinical trials were done to show the effectiveness of developed system for hemiplegic patients, who are caused by CVA and aged 50 or above. The informed consents of all subjects were obtained beforehand. In the clinical trial, the patients were divided into two groups, 5 patients treated with traditional exercise by therapists and 6 patients treated with exercise using this system The both rehabilitation time were 20 [min]. A clinical trial was executed for about one month every working day at the Gifu Central Hospital.

We made inquiries to the patients about the system's performance, as shown in Table I. As a result, evaluations with good impression were obtained. On the usual evaluation of rehabilitation, mFIM(motor Functional Independence Measure) improved significantly by comparision with traditional exercise despite the small number of subjects. However, the statistically-significant difference between two groups had not been shown on the other evaluation items since neither a number of subjects nor period were unsatisfactory.

TABLE I

RESULTS OF QUESTIONNAIRE TO PATIENTS

	1st patient	2nd	3rd	4th	5th
Q.1	1	2	2	3	1
Q.2	1	3	3	3	2
Q.3	3	3	3	3	3
Q.4	1	3	2	-	1
Q.5	1	3	2	-	1
Q.6	2	4	2	3	2

Q.1 is "How about your motivation to the rehabiritation therapy from now?". Q.2 is "Did you think that the device was safe?". Q.3 is "How did you feel about the supplementary power?". Q.4 is "Did you think that the exercises were effective?". Q.5 is "Did you think that the exercises are fun?". Q.6 is "Did you think that the exercises are suited for long period (e.g. more than two months)?" A.1 is "1. Very high, 2. High, 3. Normal, 4. Low, 5. Very low." A.2 is "1. Very good, 2. Good, 3. Average, 4. Poor, 5. Very poor". A.3 is "1. Too week, 2.Week , 3. Suitable, 4. Strong, 5. Too strong" A.4 is "1. Very good, 2. Good, 3. Average, 4. Poor, 5. Very poor". A.5 is "1. Very fun, 2. Fun, 3. Average, 4. Not fun, 5. Not fun at all". A.6 is "1. Very suitable, 2. Suitable, 3. Average, 4. Not suitable, 5. Not suitable at all". "-" is remain unanswered.

V. CONCLUSIONS AND FUTURE WORKS

A virtual reality-enhanced hand rehabilitation support system with a symmetric master-slave motion assistant has been

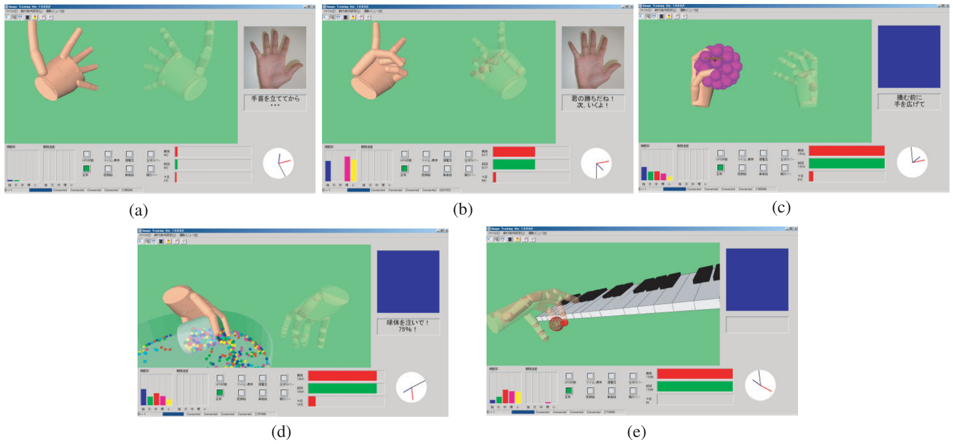


Fig. 3. Virtual Reality system: (a) *Measurement of movable range*,(b) *Scissors-paper-rock*,(c) *Pinching (or grasping) fruit*,(d) *Pouring movement*,(e) *Tapping a ball makes piano sounds*.

presented for self-performing rehabilitation therapies. In this system, individual finger joint motion of an impaired hand is supported by the exoskeleton device, which is controlled by the finger joint motion of the patient's healthy hand. A VR environment displaying an effective exercise was created in consideration of system's characteristic and based on the advice provided by the clinician researchers. To verify the effectiveness of this system, the clinical test was executed for six patients. As a result, the system contributed to improve and enhance the patient's motivation for the rehabilitation, however since neither subject nor period were enough, it did not come to show the statistically-significant effectiveness of the system.

We are convinced that the developed rehabilitation system has a high potential for self-performing rehabilitation therapy for hand-disabled persons with hemiplegia. As the future work, we are planning to improve quality of the system and to evaluate the recovery effect by conducting a clinical trial on more patients.

VI. ACKNOWLEDGMENTS

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