HAND REHABILITATION SUPPORT SYSTEM BASED ON SELF-MOTION CONTROL, WITH A CLINICAL CASE REPORT

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ABSTRACT

This paper presents a virtual reality-enhanced hand rehabilitation support system with a symmetric master-slave motion assistant for independent rehabilitation therapies. This system consists of a hand exoskeleton device and a lateral symmetric master-slave motion assistant system joined with a virtual reality (VR) environment. 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. Furthermore, a VR environment displaying an enjoyable exercise was introduced. To verify the effectiveness of this system, a clinical trial was executed using one subject.

KEYWORDS*:* Hand rehabilitation, Exoskeleton device, Master-slave, Virtual reality

1. INTRODUCTION

The number of patients with a disability in a certain part of the body as a result of a CVA (cerebral vascular accident) or bone fracture has increased in recent years. These patients need timely and persistent rehabilitation to recover their lost ability and regain their normal daily lives. Given the relative shortage of therapists, long rehabilitation training sessions with them 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 independently.

Many systems for hand rehabilitation have been studied. Functional electrical stimulation (FES) [1][2] has been proven to be a valuable tool in the restoration of hand function to patients, but this approach is not suitable for self-performing rehabilitation therapy. Virtual reality-based stroke rehabilitation [3] has shown the effectiveness of virtual reality technology for hand rehabilitation therapy, but the proposed exoskeleton device cannot support an individual patient’s finger joint motion. Most disabilities caused by CVAs are hemiplegic; that is, only one hand is impaired. Arm rehabilitation therapy with the aid of a robot [4], providing for bimanual, mirror-image, patient-controlled therapeutic exercise, is one type of self-performed rehabilitation. These therapies, however, are limited to hand motions such as gripping and tapping and arm motions. To enhance the quality of life of patients with hand impairments, a rehabilitation therapy for manipulation function and fine motion is needed [5]. Moreover, evaluation of movable joint angle, speed, fractionation, and finger strength is needed for hand rehabilitation therapies. Some devices to measure finger joint motion [6][7] have been presented, but it is preferable that any rehabilitation support system also be able to measure the motion.

This paper presents a virtual reality-enhanced hand rehabilitation support system with symmetric master-slave motion assistance. A concept of the proposed rehabilitation system, the design of the exoskeleton device, the VR environment, and the evaluation results of the subject’s functional recovery are presented.

2. FINGER MOTION ASSISTANT DEVICE

2.1 Requirements

During hand rehabilitation, the therapist extends and flexes each finger joint independently within its movable area many times. What is required instead is a device to assist such independent finger motions. In light of this need from the field of hand rehabilitation, we here developed a rehabilitation instrument to assist in the flexion/extension as well as the adduction/abduction of both the MP and PIP joints of each finger. In addition to the independent finger motion assistant, we took three requests into consideration in the design of the device:

- Flexibility to allow patients with different hand sizes to use the device
- Safety
- Ease of attachment

Regarding flexibility, an exoskeleton device constructed of closed loops with the finger is adopted. To address the safety issue, the power of the actuators is carefully designed so that the device does not cause injury. Finally, Velcro straps are utilized to fix the fingers to the device. Although there are three joints in the figure, i.e., the MP, PIP, and DIP (distal interphlangeal) joints, we studied only the MP and PIP joint, since the DIP joint moves indirectly together with the PIP joint.

2.2 Exoskeleton Device

To avoid mechanical interference, the rotation axis of the finger should coincide with that of the exoskeleton device. This requirement will be achievable for the DIP joints and PIP joints by arranging the mechanisms parallel to the finger. However, this is impossible for the MP joint, because no space is available for the mechanisms at the side of an MP joint. So we here propose an exoskeleton device as shown in Fig. 1 to maintain a wide movable range of the finger's joints without interference. One feature of this exoskeleton device is that the device forms the closed loop with the human finger as shown in Fig. 2. Two joints, whose angles are denoted by θ_1 and θ_5, are active, while the others are passive. Although it is not shown in the figure, an active joint is prepared for the adduction/abduction. Therefore, three actuators are necessary to drive this device. These actuators employ DC motors because they are compact and easily controlled.

According to the geometrical properties of the parallel mechanisms, the MP and PIP joint angles are uniquely determined by θ_1 and θ_5, respectively. For example, we discuss the relationship between θ_1 and θ_{f1}. In Fig. 2, two equations are satisfied on the Cartesian coordinate,

$$\begin{cases} x = a_1 \cos\theta_1 + a_2 \cos(\theta_1 + \theta_2) = X + L_1 \cos(\theta_{f1} - \phi_1) \\ y = a_1 \sin\theta_1 + a_2 \sin(\theta_1 + \theta_2) = Y + L_1 \sin(\theta_{f1} - \phi_1) \end{cases}$$

where, ϕ_1 and L_1 satisfy $\tan\phi_1 = a_3 / f_1$ and $L_1^2 = a_3^2 + f_1^2$. Here, the lengths of links a_1 and a_2 and the half finger length between joints f_1 are a constant and θ_1, θ_2, θ_{f1} are variables. The device has only one degree of freedom (DOF) because there are three variables and two constraints. By eliminating θ_2, θ_1 is uniquely determined by θ_{f1} and vice versa while considering the continuity of the configuration changes, which is achieved by avoiding the singular configurations. We can obtain a similar relationship between θ_5 and θ_{f2}. This property allows us to

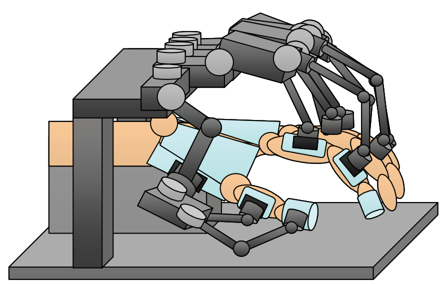


Fig.1 Image of exoskeleton device

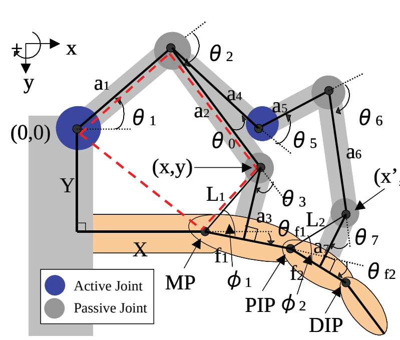


Fig.2 Device model

detect the finger joint angles without any other measureme nt devices.

To avoid singular configurations, as shown in Fig. 3, in which the configulation of a quadrangle turns into a triangle, we adequately determined the length of each link a_i (i=1-7). The singular configuratio n is avoided if and only if θ_1 monotonically varies with the MP joint angle (θ_{f1}) and so do θ_5 with θ_{f2}. To adequately select a_i's, the monotonic relationships between them can be obtained as shown in Fig. 4, where the MP joint angle changes from -45 to 90 [deg]. To accommodate different hand sizes, we made lengths X and Y adjustable.

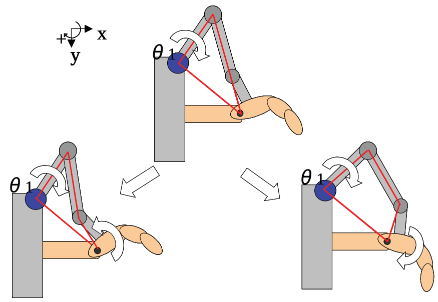


Fig. 3 Singular configuration

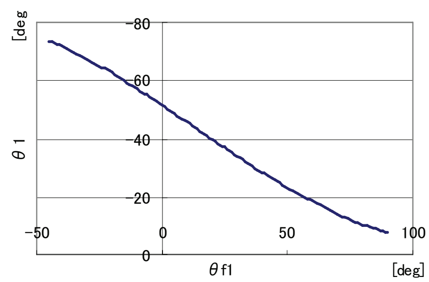


Fig. 4 Relation θ_1 and θ_{f1}

During hand rehabilitation, therapists pay attention especially to the magnitude of their assisting forces on flexion or extension of the patient's fingers. The acceptable torque for assistance is determined from the experiences of the therapists. The maximum safe joint torques to extend or flex, according to two therapists, are measured by using a torque gauge as a substitute for a patient finger. The results of the measurements are summarized in Table 1. According to these data, the adequate torques in the device are designed as follows; extension/flexion MP and PIP joints is 11 and 20 [Nm], respectively, and adduction/abduction of MP joint is 22 [Nm].

Our prototype device is shown in Fig. 5. It assists the flexion/extension of the MP and PIP joints, as well as adduction/abduction of the MP joint. This device contains "asymmetric differential gears" developed in our laboratory for an anthropomorphic robot hand [8]. These gears make the device compact while keeping two rotation-axes (flexion/extension and abduction/ adduction) orthogonal.

Table 1 Acceptable torque for fingers as estimated by therapists' experiments

Joint		Thumb [Ncm]	Index [Ncm]
CM	Extension	29.3	
	Flexion	29.0	
	Abduction	32.8	
MP	Extension	13.0	24.7
	Flexion	26.0	29.3
	Abduction	-	16.7
PIP	Extension		28.7
IP/ DIP	Extension	22.3	17.7
	Flexion	24.8	19.7

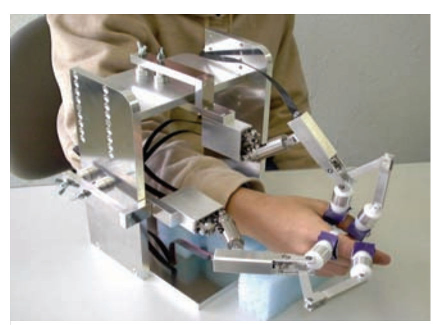


Fig. 5 Finger motion assistant device

3. SELF-MOTION CONTROL

3.1 Concepts

Most patients who need hand rehabilitation are disabled only on one side of the body. With that in mind, we propose a lateral-symmetric master-slave system using self-motion control as a motion assistant device. The normal side of the patient's hand produces the reference motion for the exercise as the master system, while the slave system, i.e., 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. 6. The symmetric master-slave control for arm motions [4] has already been presented, 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 finger movements with many DOFs, which we are considering in this paper.

The concept of the lateral-symmetric master-slave control will bring the following advantages to hand rehabilitation:

- 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 will be similar in size and structure.
- Patients can imagine the training motions for the 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.
- The master motion of the normal side prevents the atrophy of disused muscle on that side; such atrophy would occur even in the normal hand if not used sufficiently.

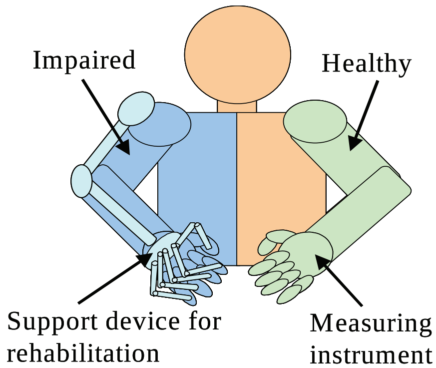


Fig. 6 Symmetric master-slave system

4. EXERCISE WITH VIRTUAL REALITY

Virtual reality (VR) simulation is utilized to incorporate amusement into the rehabilitation system. Rehabilitation is a painful exercise even if patients control the motion device. However, the VR simulation could prevent patients from getting bored during painful exercise. The VR environments are constructed using OpenGL. Graphical images of both hands are displayed. The fingers in the healthy hand are depicted based on the actual angles of that hand as measured by the data glove. On the other hand, the fingers in the impaired hand are calculated from the joint angle of the motion assistant device by solving the forward kinematics of the mechanism. We provide some VR environments that contain gaming elements. Fig. 7(a) shows pinching training simulation, i.e., flexion of finger simulation. In this simulation, when the tips of the impaired hand's thumb and index finger come close to each other, the color of an object to be grasped (a piece of fruit) will turn translucent. When the tips become closer still, the object will disappear and the trial is completed. Fig. 7(b) shows an extension training simulation. In all these simulations, when a trial is completed, the subject is awarded a point. The accumulation of points will help motivate the patient.

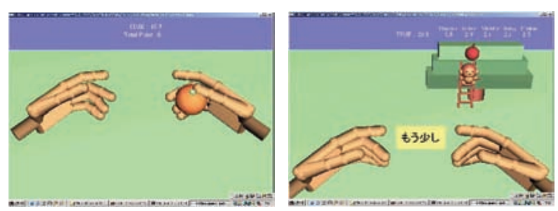

(a) Pinching training (b) Extension training

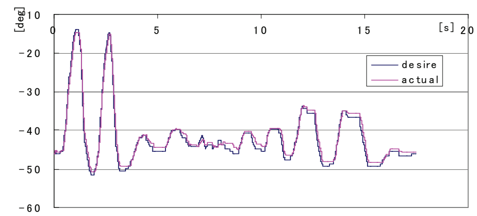
Fig.7 Training simulation

5. DEVICE PERFORMANCE

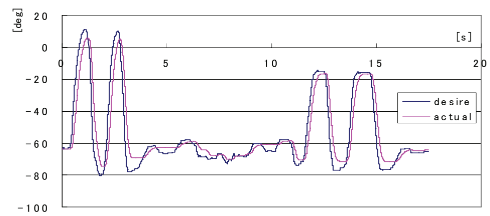
The self-motion control of the motion assist device is implemented. To measure the joint angles of the healthy hand's fingers, a data glove (Cyber Glove, by Immersion Inc.) is utilized. On the other hand, the joint angles of the mechanism are detected from the rotary encoders installed in the DC motors. The system's performance is evaluated experimentally by normal healthy subjects. In this experiment, the left hand is used as the master side, while the right is the slave side. The data of the left hand motion are measured every 15[ms] by the data glove, while those of the right hand motion are measured every 1[ms] and feedback control is applied every 1[ms]. To control the motion assistant device, PD control with gravity compensation in the joint space is applied. The motion data of the index finger are shown in Fig. 8. This figure shows that the joint angles of the motion assistant device follow the desired trajectories generated from the measurement of the data glove. Similar results have been obtained from thumb motion. Consequently, this device achieves almost the same right hand motion as the left hand one.

6. CLINICAL TRIAL

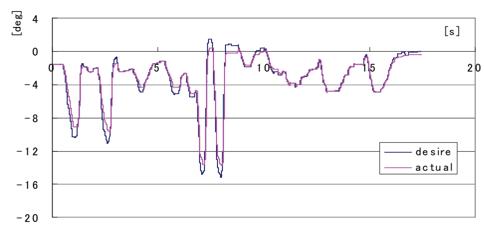
The clinical trial was executed for a 60-year-old female patient who was having trouble on the right side of the body after a cerebral stroke three weeks earlier. Informed consent was obtained from the subject beforehand. In the clinical trial, the subject received two kinds of rehabilitation. One was the traditional rehabilitation given by therapists and the other was the rehabilitation using this system. The traditional rehabilitation time was 20 [min], and that of hand rehabilitation was 3 [min] in the traditional rehabilitation. On the other hand, rehabilitation time using this system was optional; the subject could spend rehabilitation time freely. A clinical trial was executed for about one month every working day at the hospital. The movable ranges of finger joints, the maximum angular velocities of the finger joints, and the maximum finger velocity were measured. In the clinical trial, the subject's impaired finger motion was measured by this simulation and a goniometer, a measurement instrument generally used in rehabilitation therapy. The subject's movable ranges of impaired finger joints before and after the clinical trial are shown in Fig. 9. This figure shows that the ranges of motion of the impaired finger joints improved. Also improved were the angular velocities of the finger joints and the finger velocity.



(a) MP joint ( )



(b) PIP joint ( )



(c) Adduction and abduction

Fig.8 Experimental results

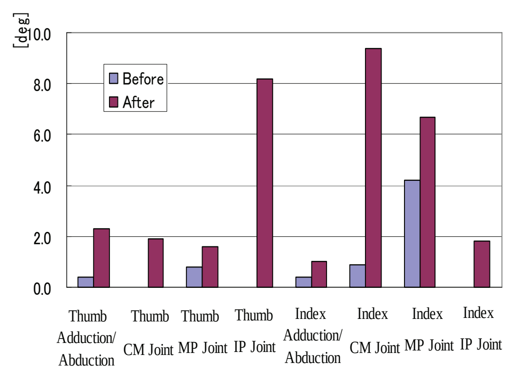


Fig. 9 Change in movable range of finger joint

We asked two occupational therapists to evaluate whether this device's performance qualified it for use in actual rehabilitation exercise. They commented as follows.

- The device would be helpful for stroke patients in their flaccidity period.
- The force supplied to assist the subject's motion was a bit small.
- The reproducible pinching motion is a side pinching. It is desirable to reproduce an oppositive pinching.
- Recovery is faster than expected when the system is used.
- Motion recovery occurred not only in the hand but also in the arm.

The subject commented that the device supported her ability to move the impaired hand, and she felt that she could move her impaired finger herself, albeit a little, only when she used the system.

7. CONCLUSION

A virtual reality-enhanced hand rehabilitation support system with a symmetric master-slave motion assistant has been 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. Furthermore, a VR environment has been introduced to make the training enjoyable. To verify the effectiveness of this system, the clinical trial was executed for one subject. As a result, the function of the subject's impaired hand improved. The findings suggest that the developed rehabilitation system has a high potential for self-performing rehabilitation therapy for hand-disabled persons with hemiplegia.

We are planning to expand this system for the rehabilitation of five fingers and to evaluate the recovery effect by conducting a clinical test on larger numbers of patients.

8. ACNOWLEDGMENT

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