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A hand rehabilitation support system with improvements based on clinical practices

Satoshi Ito * **Yasuhiko Ishigure** ** **Satoshi Ueki** ***
Jun Mizumoto **** **Yutaka Nishimoto** † **Motoyuki Abe** ‡
Haruhisa Kawasaki §

* *Gifu University, Yanagido 1-1, Gifu 501-1193, Japan (e-mail: satoshi@gifu-u.ac.jp)*
** *Marutomi Seiko Co. Ltd., Seki, 501-3936, Japan. (e-mail: ishigure@marutomi.co.jp)*
*** *Gifu University, Yanagido 1-1, Gifu 501-1193, Japan (e-mail: s_ueki@gifu-u.ac.jp)*
**** *Marutomi Seiko Co. Ltd., Seki, 501-3936, Japan. (e-mail: mizumoto@marutomi.co.jp)*
† *Gifu University, Yanagido 1-1, Gifu 501-1193, Japan (e-mail: yutaka@gifu-u.ac.jp)*
‡ *Seijo University, 2-172 Fukinodai, Tokai, 476-8588, Aichi, Japan (e-mail: abe-m@seijoh-u.ac.jp)*
§ *Gifu University, Yanagido 1-1, Gifu 501-1193, Japan (e-mail: h_kawasa@gifu-u.ac.jp)*

Abstract: We are aiming at developing a hand rehabilitation support system that provides a rehabilitation environment where patients can conduct enjoyable trainings by themselves as much as they want. First of all, the feature of this rehabilitation support system is explained with its design concept. Next, problems that came into the open by the verification test in the clinical practice are described. Two main problems are: (1) the structure of the thumb opposability assistance mechanism sometimes avoids patients from safely attaching their affected hand to the motion assistance device, (2) the connection between the affected hand and the motion assistance device requires much time and often disconnected. For the first point, we improved it by designing new thumb motion assistance mechanism with the double parallel-link structure. For the second one, the attaching method using magnetic force is introduced. The effects of these improvements are reported with experimental results.

Keywords: rehabilitation, motion assistance, master-slave control, mechanical design

1. INTRODUCTION

In this project, a hand rehabilitation support system is developed (Ito et al. (2007); Kawasaki et al. (2007); Ueki et al. (2008)). Stroke patients in the acute stage are selected as the target of this system. The cerebrovascular disease including strokes is ranked as the third most cause of death in Japan (Health and Ministry (2008)). Though the death toll of the cerebrovascular disease tends to decrease, its actual count is kept beyond one hundred thousand (Health and Ministry (2007)). Even if patients of the cerebrovascular disease can escape death, they sometimes suffer from aftereffects like hemiplegia.

Because of this situation, we aim at developing a hand rehabilitation support system: its design concept is to provide a rehabilitation environment in which stroke patients can conduct enjoyable trainings by themselves as much as they want. In the next section, the hand rehabilitation support system developed in this project is introduced at first. Then, two problems that came out into the open by the verification tests in a hospital are described: the structure of the thumb opposability assistance mechanism and a method for attaching the affected hand to the device. The section 3 reports a solution of the former problem, while section 4 of the latter. Finally, the paper is concluded in section 5.

2. A REHABILITATION SUPPORT SYSTEM

The hand rehabilitation support systems for fingers and thumb have not been developed so much (Sakai medical (2009); Wege et al. (2005); Mulas et al. (2005)). Haptic devices that is sometimes used in the research field of virtual reality has a similar structure (Choi and Choi (2000); Bouzit et al. (2002); Koyama et al. (2002)). These devices provide the sense of force to an operator who manipulates some objects in the virtual space constructed in the computer display. The forces produced by the haptic devices are, however, usually unilateral, i.e., limited to the extensional direction: The hand rehabilitation requires the bilateral assistance. Furthermore, the assistance forces

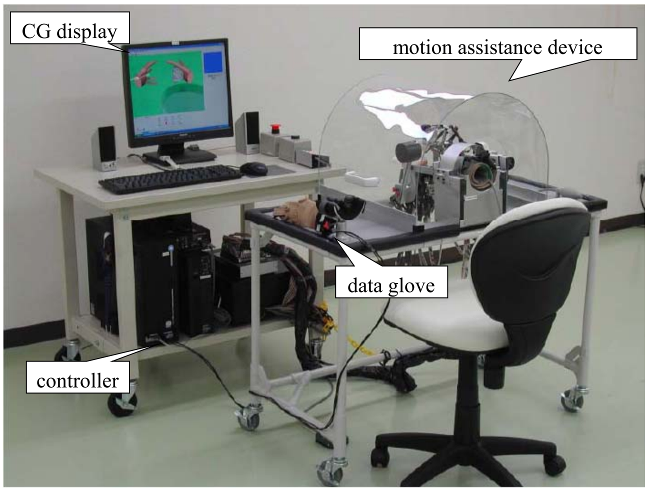


Fig. 1. System overview.

for the hand rehabilitation are usually larger than haptic feedback forces and thus firmer structures are required. Although the CPM for hand (Sakai medical (2009)) has already been offered commercially, its application restricted for fingers, i.e., it does not achieve the thumb motion assistance. Some devices under development can assist the extension/flexion of the thumb (Mulas et al. (2005)), but they have not achieved the assistance of the opposable motion of the thumb yet.

Healthy persons can move each finger and thumb individually. In addition, the thumb opposability allows them to manipulate some objects with dexterity. To recover such practical finger motions, stroke patients must take lots of rehabilitation exercises. However, even though they want to do more exercises, sufficient medical cares cannot be supplied in the current clinical practices due to the unbalances in the number of patients and doctors/therapists. Thus, we set the objective of our project to provide to the patients many opportunities of hand rehabilitation that includes the exercises with fine functional motions. From these point of view, the specification of the motion assistance mechanism of the hand rehabilitation support system here was set so that it can achieve:

- independent motion assistance for each finger and thumb.
- independent motion assistance for each joint in the same fingers and thumb.
- bilateral motion assistance, e.g., extension/flexion.
- assistance of the thumb opposability.
- wrist joint assistance.

Followed by this specifications, a motion assistance mechanism with 18 DoFs (Degrees of Freedom of motion) was constructed: 3 Dofs for 4 fingers (abduction/adduction of MP joint, extension/flextion of MP and PIP joints), 4 DoFs for thumb (abduction/adduction of CM joint, extension/flexion of CM, MP, PI joints), 2 DoFs for wrist motion assistance (abduction/adduction and pronation/supination).

2.1 Self-motion control (Kawasaki et al. (2007))

Due to many degrees of freedom of motion, the developed device must carry lots of actuators to drive them. Then, how the commands are generated for so many actuators becomes a crucial problem. To solve this problem, we focus on a characteristic of the stroke patients, hemiplegia: although the hand in the affected side is difficult to move, the hand in the opposite side is freely controlled by patient's will. To make the most use of this characteristic, the concept of a "self-motion control" was proposed (Ito et al. (2007)), in which the affected (immobile) hand is symmetrically assisted by the assistance motions generated by the unaffected (normal) hand. The following effects are expected to this method:

Fig. 2. Motion of the thumb.

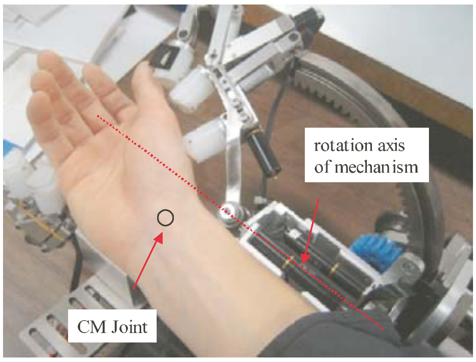
- Because the hand is usually symmetrical in the both sides, the assistance motion never exceed its range of motion (ROM).
- Patients can stop the assistance motion by themselves if they catch a scent of danger or feel pain during the training.
- Patients can exercise with understanding the timing or amount of the finger extension/flexion in the affected hand through the somatic sense of unaffected hand motion, which could facilitate the recovery of the affected hand motion.

These are reasons why we adopted this method for the hand rehabilitation system. Regarding to the last term, the similarity to the mirror therapy is sometimes pointed out. To examine the effects of this symmetrical motion training introduced in this system is an important object of the verification tests in the clinical practice.

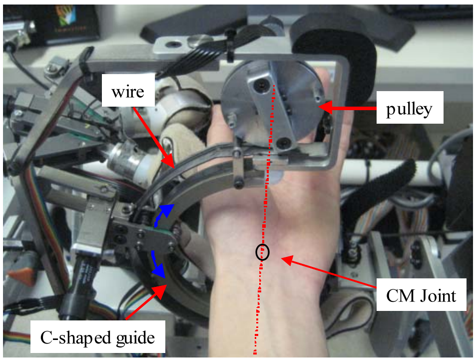
2.2 Image training function (Ueki et al. (2008))

The affected hand are assisted by the mechanism followed by one's own unaffected hand motion. In many cases, however, patients do not know which motions are effective as the rehabilitation exercises. Especially, we aim at providing the rehabilitation environment in which patients can do exercises alone: there, no doctors or therapists advise them on the training menu. Therefore, some schemes are required so that the patients can generate adequate motions for exercises without doctors' or therapists' instructions.

From this aspect, we introduce a multi-modal instruction method using computer graphic images as well as voice announcements. They are provided as the following five training programs: Pinch-the-fruit, Rock-paper-scissors, Play-the-piano, Pour-beads and ROM measurements. They are selected from the medical point of view. The Pinch-the-fruit aims at producing the extension/flexion in the affected hand. The Rock-paper-scissors and the Play-the-piano are for facilitating disjunctive and separated movements and the Pour-beads, the training of the finger-wrist coordination. The ROM measurements are



First test model.



Version in verification tests

Fig. 3. Structures of the previous mechanisms.

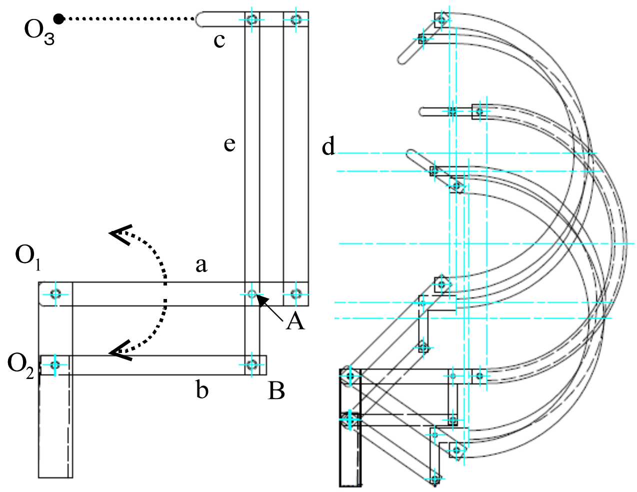
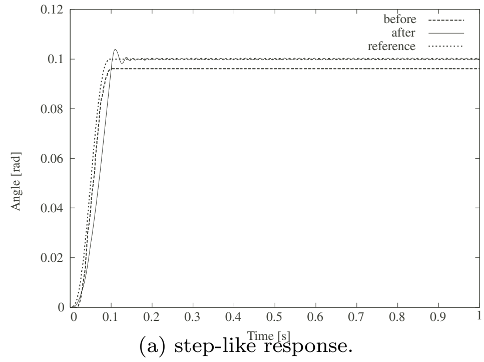


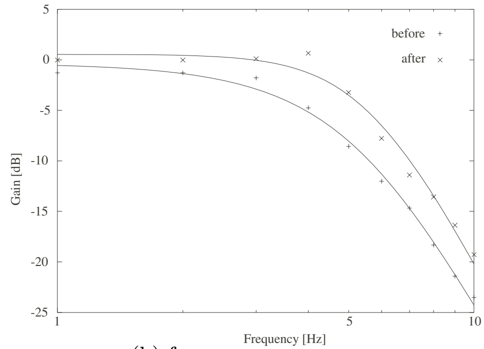
Fig. 4. Double parallel link structure.

necessary tasks to evaluate the recovery of the affected hand motions. A noticeable advantage in the use of the motion assistance device is found in that the ROM can be obtained during the exercises based on the kinematic relations of the link mechanisms of the device.

The simple repetition of the exercises bores the patients. In order to enhance or keep their motivations for rehabilitation, a game element was introduced. The affected hand motions during the exercise are scored in terms of the time for the task accomplishment, or the amount of the extension/flexion angles. This score as well as their past records are shown in the computer display with the encouraging vocal announcements.



(a) step-like response.



(b) frequency response.

Fig. 5. Comparison of the thumb motion assistance device.

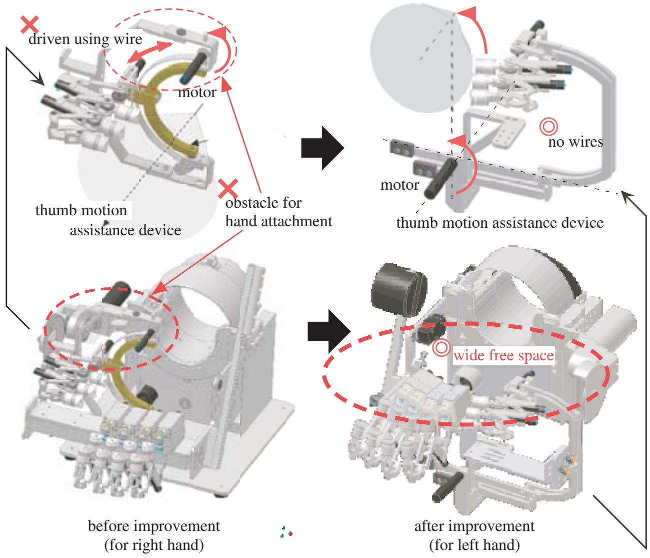


Fig. 6. Change in the mechanism for thumb motion assistance.

2.3 A total system

The developed rehabilitation system is shown in the Fig. 1. The data glove (Cyber Glove, Immersion Corporation) is used to measure the motion of the unaffected hand. Refer to the previous papers (Kawasaki et al. (2007); Ueki et al. (2008)) for the detailed design.

2.4 Verification tests at the clinical practice

To verify the effect of the exercises with self-motion control and for the maintenance of the patients' motivation, verification tests in the clinical practice were performed at the Gifu Central Hospital in Gifu, Japan, from the Aug.

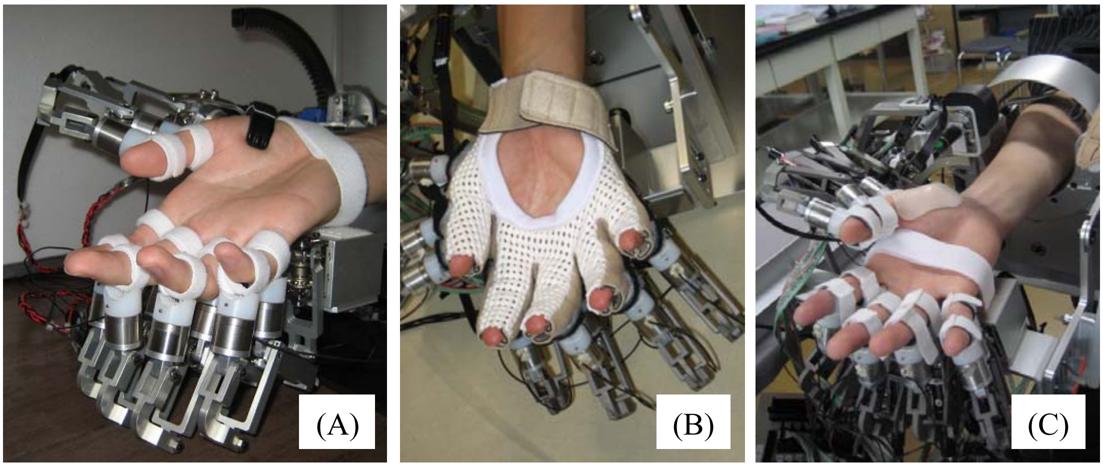


Fig. 7. Attachment methods tried in our previous works.

2007 to Feb. 2008. These tests were approved in advance at the medical ethics board of this hospital.

Six patients agreed to join to this test. Though the case patients are few, we confirmed that the exercise with self-motion control is no less effective than the conventional rehabilitation method without significant difference. However, we did not obtain evidences that this method more promotes the recovery. In order to examine the motivation maintenance, we asked the patients to complete an evaluation form with some questionnaires. Then, the questionnaire, "Do you think the training is effective?" and "Do you think the training is enjoyable?" obtained high-scored answers. The population of this test may be somewhat biased since they all agreed to use and had interest in our rehabilitation support system. However, these data explicitly ensure that the enjoyable rehabilitation environment is provided thanks to the image training function with the game element.

These verification tests revealed the following two problems: the structure of the thumb opposability assistance mechanism and the method for attaching the affected hand to the motion assistance device. In the remainder of this paper, the improvement of the above two problems is discussed.

3. STRUCTURE OF THE THUMB OPPOSABILITY ASSISTANCE MECHANISM

3.1 Thumb tip motion by CM joint

The thumb CM joint has 2 DoFs motions: extension/flexion and abduction/adduction. The latter abduction/adduction produces an arc-like motion of the thumb tip, while the former extension/flexion enables the thumb to touch a fingertips, as shown in the left of Fig. 2. To design a mechanism that assists these motions enabling the thumb opposability, the thumb motion is approximated by the cone, as shown in the right of Fig. 2: the CM abduction/adduction moves the thumb tip on the circumference of the bottom aspect of the cone, which is called here conic motion, while the CM extension/flexion does to the radius direction, called here apex motion. Then, the mechanism is designed separately for conic motion assistance and for the apex motion assistance.

3.2 Problems

The previous versions of our developed devices are shown in Fig. 3. Though the first test model shown in the top figure could achieve the conic assistive motion, the center of the assistive motion did not coincide with that of the CM abduction/adduction. This problem resulted in the major change of the mechanism, because the rotation axis of the assistance of the conic motion is definitely positioned outside the forearm: the rotation axis of the human conic motion actually goes inside the forearm. After some considerations, the C-shaped guide structure, as shown in the bottom figure, was introduced so as to coincide the conic rotation axis of the motion assistance mechanism with that of the human hand. Thanks to this improvements, the thumb opposability was successfully assisted.

However, the verification tests in the hospital newly revealed the following problems:

- The C-shaped guide structure sometimes becomes an obstacle when the patients attach the affected hand to the device, since this structure occupied large space above the mounting location of the hand.
- The response of this mechanism was not so good due to the friction that occurs when the assistance mechanism pulled by wire slides along the guide structure.

Namely, in addition to the conic assistive motion, the solution of the above two problems were required in the design of the next version.

3.3 The double parallel-link structure

In order to solve the problems in the above section, a double parallel link structure was designed as shown in Fig. 4. This structure is constructed by double-tiered parallel links, at the tip of the which the extension/flexion assistance mechanism for thumb is attached. This double parallel-link structure allows the extension/flexion assistance mechanism to always direct to its rotation center. In addition, it can be driven without wires, which reduced the effect of the frictions.

Table 1. Velcro attachment in clinical practices.

		Time for preparation (min)			interruption (times)
	days	min	max	avg ± sd	avg ± sd
A	17	5	7	5.82 ± 0.81	3.20 ± 1.93
B	29	3	8	5.21 ± 1.26	1.47 ± 1.36
C	15	4	8	5.40 ± 1.18	1.27 ± 1.62
D	12	4	7	5.25 ± 0.85	3.86 ± 1.56
E	13	4	8	5.23 ± 1.24	3.23 ± 1.17
ave.				5.40 ± 1.09	2.30 ± 1.85

3.4 Performance evaluation

The assistive force, step-like response, and frequency response were measured using the improved new structure. The averaged force was 1.55 Nm (N=5) that was almost the same as before improvement (1.56Nm (N=3)). The step-like response shown in Fig. 5(a) got better with the less stationary error and quicker response, although slight vibration was observed. The frequency response shown in Fig. 5(b) was also improved a bit.

In summary, without reducing the performance of the motion, the double parallel-link structure by no use of the wired driving mechanism can obtain enough space above the hand motion assistance mechanism as illustrated in Fig. 6, which ensure the safe attachment of the patient's affected hand.

4. ATTACHMENT METHOD OF THE AFFECTED HAND

4.1 Methods in the previous versions

In order for the mechanical device to effectively assist individual motions of finger joint, lots of the connections are required between the device and the affected hand. In this rehabilitation system, the device is connected to the thumb at the three points and the each figures at the two points as well as the back of the hand is banded to it.

Up to now, three attachment methods for connecting them were tried, as shown in Fig. 7.

(A) Some Velcro straps are fastened to the fingers and thumb. These Velcro straps are sticked to other Velcros prepared on the fixture of the motion assistance mechanisms.
(B) A glove the all the back side of which is made by Velcro is used instead of many Velcro straps.
(C) Velcro straps are mechanically fixed to the fixture in advance. These straps are fastened to the fingers and thumb.

The forearms are attached using the specially designed covers in all methods.

4.2 Problems

These methods are tried for some normal adults. The method (A) required a lot of time for binding the articulating part of the fingers and thumb by the Velcro strap. The method (B) shortened the time for attaching Velcro to the hand, but the stick forces between two Velcros were so small that the device are sometimes unfastened from the

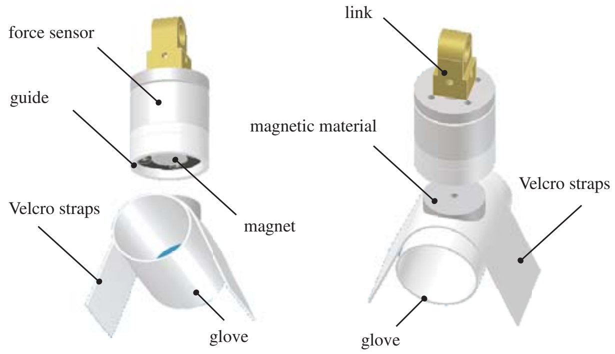


Fig. 8. Fixture design.

Fig. 9. Glove for affected hand.

hand and thus the exercises were sometimes interrupted. This was the same as the method (A).

To prevent the interruption of the exercises, the method (C) was introduced at the expense of time for attachment. This method is adopted to the verification test in the section 2.4. As a result, the Velcro straps never unstuck from the device. However, the Velcro straps came to slide to the proximal and distal direction on the finger and the device was consequently disconnected from the finger. Because the method (C) makes it difficult to re-fasten the Velcro straps, much time were taken to restart the exercise. The table 1 shows the results of the time for preparation before the exercises as well as the times of exercise interruption due to the disconnection during one set of the exercises. The time for preparation was measured in each minute. Note that almost of this time was devoted to attach the hand to the device.

4.3 Improvements

The firm attachment of the affected hand to the device is required to the effective training, but it costs much prepa-

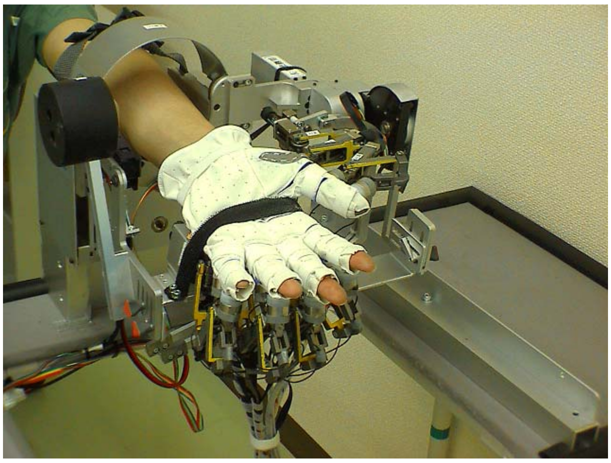


Fig. 10. Snapshot when the hand is attached in this hand motion assistance system.

Table 2. Magnetic attachment in laboratory test.

	1st	2nd	3rd	4th	5th	AVG.	S.D.
time[s]	210	222	212	188	220	210	13.5

ration time, which makes patients tired before training. To solve this conflicting problem, magnetic force is utilized in the following way.

The magnetic substance on the glove is magnetically connected to the Neodymium magnet embedded to the fixture of the motion assistance devices. The guide is designed at the tip of the fixture, as shown in Fig. 8. This guide helps the magnetic substance on the glove with exactly being attached to the connecting point on the fixture.

Because all the magnetic substances are attached on the glove, the connecting points are set on the patients' hand only by putting on this glove. To stabilize this magnetic substances, they are fixed on the aluminum supporter stitched on the glove. Thus, the magnetic substances never slide on the fingers and thumb. In addition, the Velcro straps are prepared to firmly fasten the connecting point at the magnetic substances. In order for the patients to easily put and take off the glove, it was made by elastic materials with large margin. A sample of the glove is shown in Fig. 9.

4.4 Evaluations

The time to attachment using the magnetic method was measured 5 times in our laboratory. The results are shown in Table 2. It was less than 4 minutes (240 [s]). According to Table. 1, it took 5 minutes in average in the Velcro method, implying that the time for attachment was shortened by about 1 min. Note here that the experimental conditions differ in two measurements: the therapist helped the patients to attach it in the clinical practice whereas the nonprofessional person helps the normal person to attach it in the laboratory experiment. The time measurement in the clinical practice is necessary to clarify the true effects of the magnetic method.

Regarding to the magnetic disconnection of the fingers from the devices, a couple of interruptions was required in the laboratory experiments. However, the magnetic method surely made it easy to reconnect them in comparison with the Velcro method, because it was not necessary to fasten the finger by the narrow Velcro straps.

5. CONCLUSIONS

A hand rehabilitation support system developed in our project was introduced with brief reports of the verification tests in a hospital. Based on the results of these tests, two points were improved: the structure of the thumb opposability assistance mechanism and the attachment method of the affected hand to the device. The sufficient effects of the improvement were observed in the laboratory experiments. We are planning to examine the training effect of our system as well as the effects of the improvement in actual clinical practices.

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