History of Research and Development of the Finger Joint Rehabilitation Device in Japan in the Past Decade

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ABSTRACT

With the aging society, the demand for rehabilitation medicine is diversifying, and the expectation and demand for engineering support are extremely high compared to other medical fields. For example, the role of rehabilitation equipment is broadly divided into the complementary role of health care workers involved in rehabilitation medical care and the support of family nursing ability. In the study, the rehabilitation equipment was designed and developed from an engineering point of view as one of the methods to recover the grip function at the finger joint due to sequelae such as cerebrovascular disease. In particular, grasping an object by a finger is an extremely complicated dynamic phenomenon that controls the direction and magnitude of the force generated at the fingertip by muscles and balances the force acting on the object. Development research on rehabilitation equipment is a rare technology development in the world. In this paper, we describe the transition of the research results that we have been conducting since 2006 in response to requests from medical institutions. We also propose a new hand-operated rehabilitation device for finger joints based on a number of development devices, focusing on the flexion and extension of four fingers.

Keywords: Rehabilitation equipment, Finger joint, Miniaturization, Weight saving, Simple mechanism, Flexion and Extension

1. INTRODUCTION

The first and second most common causes of death in Japan are malignant neoplasm and cardiac disorder, followed by cerebrovascular disease. However, the percentage of people who die of cerebrovascular disease has been decreasing annually[1)]. Two reasons behind this trend are as follows; one is the early detection of diseases as a result of the advancement and elaboration of medical devices owing to marked progress in medical technologies and the fusion of medical and engineering fields. The other is the improvement of treatments for patients in an acute stage.

However, the number of patients who remain alive but become orthopedically impaired is tending to increase. According to the survey results reported by the Ministry of Health, Labour and Welfare in 2008, the number of physically handicapped people in Japan is estimated to be 3,500,000. Among these, the number of orthopedically impaired people is 1,760,000, which is greater than any of the numbers of people with other disorders (vision disorder, auditory/language disorder, and internal impediment). Among orthopedically impaired people, the number of people with upper limb dysfunction is 450,000, which is the second highest after the number of people with lower limb dysfunction[2].

The rehabilitation for patients to alleviate their dysfunction is divided into two types: rehabilitation for patients in the acute phase and for those in the chronic phase. The purpose of rehabilitation for patients in the acute phase is the alleviation of and recovery from aftereffects. In contrast, the purpose of rehabilitation for patients in the chronic phase is the resumption of normal activities.

Rehabilitation is carried out at medical institutions mainly by therapists (physiotherapists, occupational therapists, and speech therapists), doctors, and nurses. After recovery, the rehabilitation carried out at institutions is replaced by independent rehabilitation carried out at home with the help of visiting therapists. However, the number of therapists and nurses involved in rehabilitation is insufficient, and no marked increase can be expected in the future. In addition, the institutions that provide rehabilitation are concentrated in large cities, and the numbers of rehabilitation institutions, therapists, and nurses in local areas are limited, causing the insufficient rehabilitation of patients[3].

Under such circumstances, the development of rehabilitation devices with which patients can independently carry out rehabilitation has been demanded. The development of small and lightweight rehabilitation devices for finger joints is important from the viewpoint of enabling patients to carry out rehabilitation anywhere[4].

It has been medically demonstrated that moving the fingers, especially the tip of the fingers, stimulates brain nerve cells, promotes brain activity, and prevents cerebrovascular disease, and thus is an effective means of rehabilitation[5),6),7)].

The number of rehabilitation devices dedicated for specific movements of fingertips is small. There are several manufacturers in Japan and overseas that have been involved in the development of rehabilitation devices for finger joints; however, the number of devices that are particularly effective for complicated and composite movement of finger joints is limited. Conventional devices are superior in terms of functionality but are large and heavy (8 kg) because they are applied to the rehabilitation of fingers, finger joints, and forearms. The operation of these devices is complicated, and the assistance of physiotherapists and helpers is necessary to attach and operate these devices during rehabilitation. In addition, these conventional devices are expensive[6),8)].

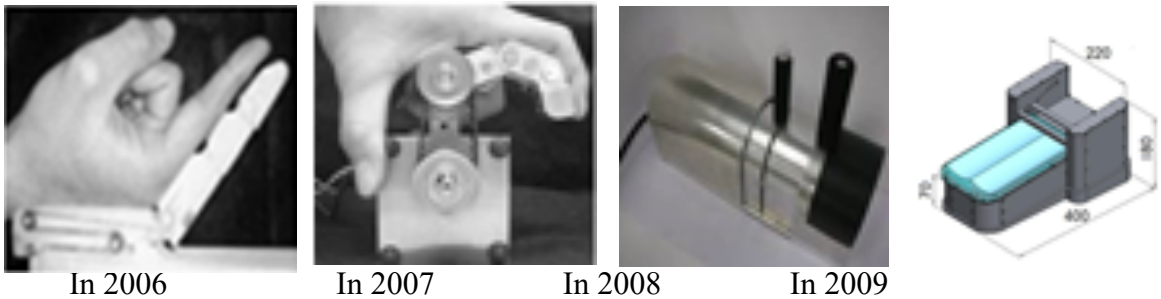
In this paper, we explain the following. (1) Since 2006, as requested by medical institutions, we have been developing small and lightweight rehabilitation devices for finger joints that can be used at actual medical sites. The history of the research and development is explained. (2) Electric power has been required for the operation of rehabilitation devices dedicated for finger

joints. However, the device that we developed in 2010 is operated manually. The characteristics of this device are also explained.

The purpose of this study is to develop a practical rehabilitation device with a simple mechanism that enables continuous rehabilitation, to examine their effectiveness, and then to demonstrate the feasibility of the developed device as a practical rehabilitation tool through a third-party evaluation of its performance and conditions.

2. HISTORY OF THIS RESEARCH

Figure.1 shows the history of the research of rehabilitation devices for finger joints[9]. The research was initiated in 2006 as requested by medical institutions. In the basic research in 2006, passive movement of fingers was clarified using a prototype device. In 2007, a device that enables rehabilitation of one finger was designed on the basis of the results of basic research and its effectiveness, and the points needing improvement were examined. In 2008, a rehabilitation device that can be used in actual medical sites was designed and developed taking into consideration the above points. Health professionals (doctors and therapists) tested the developed prototype device in actual medical sites. In 2009, for the further improvement of effectiveness and the reduction of weight, analyses of the design and operation were carried out. Through these activities, we designed and developed a new rehabilitation device for bending and stretching four fingers in 2010[10].



In 2006 In 2007 In 2008 In 2009

Figure 1. *History of the research.*

3. DEVELOPMENT AND DESIGN ON NEW DEVICE (2010)

3.1 Target users and basic operation

The target users were patients with cerebrovascular disease (or resulting nervous disorder). The target operation was continuous practice to widen the range of joint mobility to prevent the joint contracture that occurs during the recovery phase of patients with cerebrovascular disease. The dimensions of the device were decided on the basis of average finger measurements of elderly Japanese males and females[11),12),13)].

3.2 Design concept

First, the design concept of the device was examined and defined. The aim of the rehabilitation device is the improvement of the quality of life (QOL) of users in daily activities.

Therefore, the satisfaction of users is the first priority. Turning ideas into an actual device is not sufficient. It is also necessary to make the device attractive to users so that they can feel a satisfactory sense of ease and be undaunted by the design of the device.

Not many health professionals have both medical and engineering knowledge in terms of the operation and structure of devices. Both engineering and medical viewpoints are important in realizing the widespread use of a rehabilitation device. Not only developers but also users and those who manage the devices are required to become knowledgeable about the mechanism and the method of use.

The Brunnstrom recovery stage test is a typical method of objectively evaluating the effectiveness of rehabilitation. Our device focuses on four fingers. Therefore, we focused on the item "turning a doorknob" in the Brunnstrom test as an index and a quantitative standard of judgment of functional recovery. Note that the force required to turn a standard home doorknob (diameter of the grip, 50 mm) is 3.5 N·m.

We specify the following design concepts.

(1) The mechanism of the device and the method of use should be simple so as to be understood by anyone involved in the use of the device.
(2) The device should have an appearance that lessens its image as a machine and provides a sense of ease to users as well as a benign design.
(3) Continuous exercises to expand the range of finger joints, focusing on bending and stretching operations, should be possible.
(4) The device should be portable (small and lightweight).
(5) The device should be manually operable.

3.3 Design specifications

The basic specifications of the device are as follows.

1) Main body mass M1

The developed device is lighter than conventional devices. The mass of the device developed in 2008 was 7.4 kg, which was reduced to 5.5 kg (25% reduction) in the device developed in 2009 to improve the portability. However, a further reduction in the mass was considered to be necessary, and the mass of the main body of the device developed in 2010 was set to 4 kg, which is a further reduction by 25% compared with the device developed in 2009.

2) Portable mass M2

The portable mass of the main body of the device is assumed to be equivalent to(?) the mass of an arm assuming that a user fixes his/her arm to the device from the fingers to the elbow. On the basis of the average mass percentage of one arm relative to the entire body, the mass of an arm was calculated to be 2.5 kg, and this was set as the portable mass.

3) Required thrust force F1

The grip force of fingers is quantified to determine the required thrust force for the device. The required thrust force F1 is the maximum load applied to the finger driving section, which is

assumed to be the force applied to a patient by a therapist during rehabilitation. The maximum force of a fingertip when a healthy subject pushes an object is used as the required thrust force F1. The maximum force is applied by the left thumb of a healthy subject (108 N). Therefore, the required thrust force F1 was set at 110 N.

4) Required thrust force F2

The required thrust force F2 is the force required by the user to move the device forward or backward to bend and stretch the finger driving section. The device is operated manually; thus, the force of the user's arm should provide the required thrust force F1. To this end, the required thrust force F2 should be set as small as possible. The force of an arm with an elbow angle of ≤90° of a person in a seated position is typically 160 N at minimum. Therefore, the required thrust force F2 was set at 160N.

3.4 Basic operation

The target fingers are the four fingers except the thumb. The thumb moves in a direction different from that of the other four fingers and thus is excluded from the target. The most important characteristic of the device (Figure.2) is that it is operated manually. The basic principle and the method of rehabilitation are outlined below.

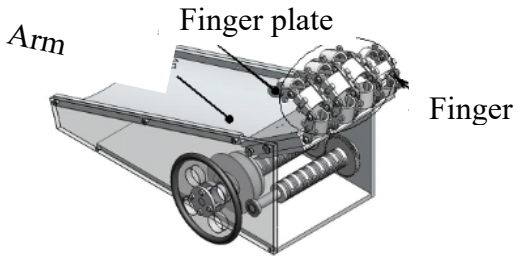
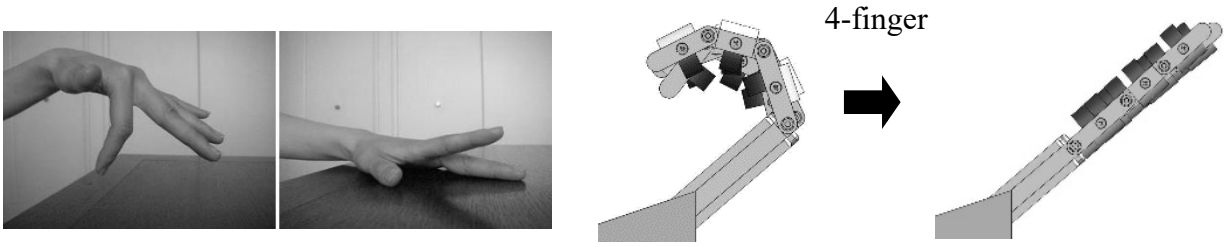


Figure 2. *Characteristic of the device*

(1) Place the right upper arm on the arm support with the palm turned upward.
(2) Fix the four fingers to the finger driving section.
(3) Secure the upper arm to the arm support.
(4) Move the main body of the device forward so that the finger driving section is bent being pulled by wires.
(5) Move the main body of the device backward to stretch the fingers.

Figure 3 shows the schematic of the bending and stretching operations of fingers using the device. The voluntary forward and backward movements of the device are applicable to symptoms of joint contracture and flaccidness of the finger joints. In addition, it is possible to set the range of joint movement as desired, leading to less pain, sense of discomfort, and anxiety.

Moreover, users can use the manually operated device anytime, anywhere because no electricity is required. The finger driving section simulates the structure of human fingers.



(a) *bending* (b) *stretching*

Figure 3. *Bending and stretching operations of fingers*

4. EXAMINATION BY RAPID PROTOTYPING (RP) AND FABRICATION OF PROTOTYPE DVICE

4.1 Examination by RP

Before fabricating a prototype device, we carried out RP of the main parts in cooperation with Professor Tsutomu Araki (Tsukuba University of Technology) to examine the assembly and shape of the prototype. Figure 4 shows a photograph of the prototype device obtained by RP. The items examined in the operation test of the prototype device and the results are explained.

4.1.1 Checking of operation

1) Move the device forward so that the finger driving section bends.
2) After bending is confirmed, move the device backward to stretch the finger driving section.
3) Repeat steps 1) and 2) to confirm the operation of the finger driving section.

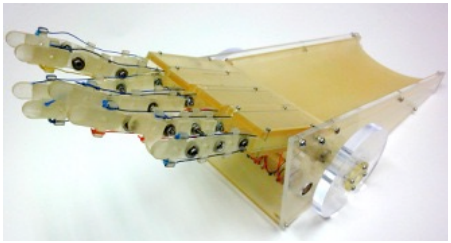
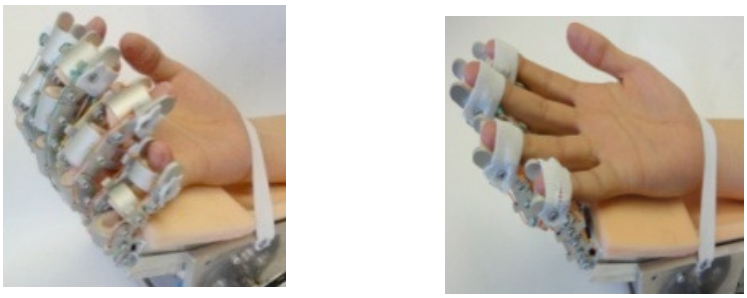


Figure 4. *Prototype device obtained by RP*

4.1.2 Results

1) The bending angles of fingers varied. To address this problem, the device was improved so that the wires would be reeled smoothly.
2) Wires loosened excessively, which led to an increase in the number of rotations of the winding drums during the bending and stretching operations. The length of idle wires was reduced so that the tension of the wires was directly applied to the winding drums.

3) Wires were not smoothly wound. The mechanism of the winding drums was improved. Figure 5 shows the bending and stretching operations of the RP prototype device.



(a) *bending* (b) *stretching*

Figure 5. *Bending and stretching operations of the RP prototype device.*

4.2 Fabrication of prototype device and confirmation of its functionality

Figure 6 shows the prototype device developed.

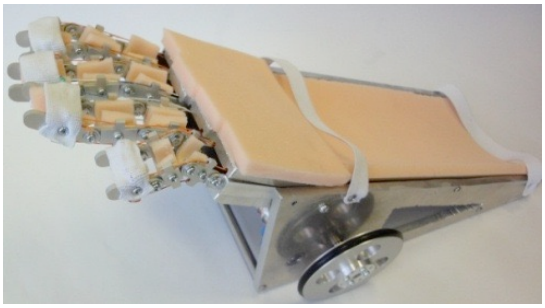


Figure 6. *Prototype device developed*

1) Safety

The conventional rehabilitation devices are driven by a motor, and safety problems related to overloading and unwanted operation may occur. With the newly developed device, the force of the arm of the user or a helper, instead of electric power, is utilized. This mechanism reduces the risk of unwanted operation; users can stop the operation of the device at their own discretion when they feel an overload. In addition, as a safety measure, a torque limiter was placed at the main shaft. The main shaft is directly connected to the wheels, which link the main shaft to the winding drum. A cutoff torque is set on the torque limiter; the torque limiter blocks the transmission of torque between the main shaft and the winding drum when a torque exceeding the cutoff torque is detected, that is, the user feels strong pain.

2) Operation test

Operations of the prototype device were tested following the procedures used for the RP prototype device.

(1) Bending commenced after the device was moved forward by 280 mm; complete bending was confirmed. Bending of the third finger was the smoothest.

(2) When the device was moved backward by 70 mm, stretching from the fingertip commenced. The stretching was not smooth; the degree of stretching varied among fingers.

(3) After repeated bending and stretching, the device did not return to the original stretched state even when the device was returned to the initial position. It is considered that even though contact between neighboring wires was prevented after the improvement, the above problem occurred because the direction of wire winding changed before a sufficient difference in tension between upper and lower wires was achieved.

5. EVALUATION OF EFFECTIVESS AND QUESTIONNAIRE SURVEY

5.1 Measurement of various parameters during operation

The difference in the position of the rotation center between the device finger and the actual finger secured on the device was measured, as were the angles of bending and extending, using a medical protractor and a ruler to judge the difference in bending and stretching operations between the device and actual fingers. The measurement conditions were as follows.

5.1.1 Measurement conditions

1） Secure fingers to the device and move the device forward for the bending operation.

2） Continue the bending operation; measure the bending angle of the device finger when the torque limiter is in effect.

3) Move the device backward for the stretching operation. Measure the stretching angle of the device finger.

4) The angle is assumed to be 0^{o} when fingers are stretched, and the angle of bending is assumed to be positive. The maximum bending angle of the device is $\pm 90^{o}$. The items measured and the results are not shown here.

5.2 Discussion of measurement results

The error in the position of the rotation center between the device finger and the actual finger secured on the device was more than 10 mm because the fingers were not perfectly fitted to the device. The error in the position of the metacarpophalangeal (MP) joint was large because the positions of the rotation center were not in agreement between the device and the finger. The error in the position of the fifth finger was also large because the fifth finger did not fit the device well. The error in the position of the MP joint was the largest, followed by those of the proximal interphalangeal (PIP) joint and distal interphalangeal (DIP) joint. Although the rotation centers of the device fingers did not agree with those of actual fingers, fingers were bent and stretched from the joints close to the fingertips. The difference in the position of the DIP joint in the bending state tended to be large, indicating that the load applied to the DIP joint by the device was the largest. The displacement among fingers in the stretched state was not uniform. Further improvement of the stretching operation of the device is required.

5.3 Questionnaire survey and results

A questionnaire survey was carried out with 12 healthy subjects for third-party evaluation of the effectiveness of the device. Table 1 shows a summary of the results.

The subjects were instructed to answer the questionnaire on a five-point scale (5, good; 1, poor). Regarding the size of device (questionnaire items 2, 4, 5, and 6), 5 means too large, 3 means moderate, and 1 means too small. Regarding the mass of the device (questionnaire item 3), 5 means too heavy, 3 means moderate, and 1 means too small. Regarding questionnaire items 8 and 9, 5 means too strong, 3 means moderate, and 1 means too weak.

Table 1. *Results of questionnaire survey.*

No.	Questionnaire items	Evaluation
1.	Is the device attractive?	3.4
2.	Is the size of the device appropriate?	3.8
3.	Is the mass of the device appropriate?	3.9
4.	Is the size of the arm support appropriate?	3.8
5.	Is the size of the hand-securing cradle appropriate?	3.9
6.	Is the size of the finger-securing rods appropriate?	2.3
7.	Is the device easy to move?	2.8
8.	Is the force during bending appropriate?	2.9
9.	Is the force during stretching appropriate?	2.6
10.	Do you feel uneasy during the operation of the device?	4.0
11.	Is the mechanism of the device easy to understand?	4.3
12.	Do you think effective rehabilitation is achieved using the device?	3.4
13.	Do you think you can use the device for a long period of time?	2.9
14.	Is the device easy to operate?	4.4
15.	Do you think the device is applicable to patients requiring rehabilitation?	2.1

As shown by the questionnaire results, many respondents considered the device to be too heavy and the size too large. The stretching strength of the winding drum above the torque limiter was considered appropriate, and the device satisfactorily assisted bending and stretching operations without applying additional load. Respondents evaluated the mechanism and driving method of the device as being easy to understand, satisfying the basic concept of a simple rehabilitation device. However, the appearance and sense of ease(?) were unsatisfactory. In the future, we plan to improve the device by reducing the sense of anxiety caused by its appearance so that it will be better received by users.

6. CONCLUSION

With the arrival of an aging society, the importance of medical rehabilitation devices has been increasing. Among them, the number of studies on the practical use of rehabilitation devices for lower limbs has been increasing; however, the number of studies focusing on rehabilitation devices for upper limbs, particularly the fingers, has been limited.

Under such circumstances, we have designed and fabricated, by RP, a prototype device that can continuously and manually support bending and stretching operations of the fingers

without the need for electrically driven motors, on the basis of the basic concept of a small, lightweight, and easy-to-operate rehabilitation device.

The device was made primarily for the elderly, and the dimensions of the fingers were precisely simulated using the data in the Handbook for Standard Figures and Equations Based on Human Engineering. The operation and mechanism were confirmed by RP in advance of fabricating a prototype device. Thus, points to be improved were identified before fabricating a prototype device, leading to smooth fabrication. The following are the main points in this study.

1) A rehabilitation device that can simulate the movement of human finger joints and that fit the actual dimensions of human fingers was designed and developed. A prototype device based on the design concept, which was revealed from the results of a questionnaire survey, was developed.

2) The operation and fit of the prototype device were examined. It was found that the prototype device supports bending and stretching operations of fingers, demonstrating its effectiveness as a rehabilitation device.

3) From the questionnaire survey, reasonable evaluations of the appearance, size, mass, the sizes of the arm support and hand-securing cradle, the mechanism, and the operation method, were obtained. However, the attractiveness of appearance and the alleviation of unease, for example, should be further improved, considering the practical use by patients.

4) We developed, for the first time, a manually operated rehabilitation device dedicated for finger joints. A prototype device was fabricated, and its validity as a rehabilitation device was demonstrated by measuring its effectiveness.

In this study, we endeavored to integrate engineering and medical knowhow. It is necessary to develop a rehabilitation device with an easy mechanism that enables continuous rehabilitation so that the gap between engineering and medical aspects is narrowed. In subsequent studies, we are planning to carry out an overall evaluation of the rehabilitation device toward its practical use after conducting effectiveness evaluations with medical professionals and the elderly.

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