Robotic Finger Rehabilitation Support Device for Home Use—An Analysis of the Effect of Finger Rehabilitation for the Upper Limb Function Recovery

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***Abstract*—As the number of patients suffering from cerebrovascular disease (CVD) increases, it is desired that the patients will be able to receive proper rehabilitation at home without specialists' help. For this, we have developed a finger-dedicated robotic rehabilitation support device that is compact enough to be used at home. The device induces voluntary muscular contraction at a finger by the help of power assisted finger lifter. The lifter is a simple lever on which the patient places his/her finger. Although the mechanism is simple to be used at home, there is a question whether applying only a finger-dedicated rehabilitation is sufficient to improve the quality of life of a patient including recovery of upper limb functions. To answer this question, we conducted experiments that show skill transfer from finger to elbow. In the experiments, subjects are asked to train to produce a specified force at their fingers. After training, it was shown that the subjects are able to perform the same skill by using elbow, where no training was performed. The results support that the finger-dedicated rehabilitation would be appropriate as a target for a robotic home rehabilitation device.**

***Index Terms*—cerebrovascular disease; feel of weight; finger rehabilitation; home device**

I. Introduction

Today, as much as 1.3 million patients have been suffering from cerebrovascular disease (hereinafter CVD) in Japan [1]. However, the number of medical institutions are insufficient to the increasing number of CVD patients. This causes shorter duration of the treatment in hospitals for patients. In Japan, after 180 days from the onset of this disease, the patient will be regarded as his/her disabilities fixed. By this, after this period, very limited rehabilitations, such as only13 units (20 minutes for each unit) per month, are allowed in a hospital. Without frequent rehabilitation, a comprehensive deterioration of the body function may proceed. This causes protracted motor weakness, which may restrict activities of daily living (hereinafter ADL) forcing inconvenient home and social life.

From this point, a home rehabilitation device, which supports rehabilitation without a specialist’s help, is needed. Currently, a number of rehabilitation support robots have been proposed. However, most of these are aiming at lower or upper limb function recovery, which are too expensive or too heavy to be used at home.

One of the good targets for home rehabilitation automation is a finger rehabilitation. Fingers play a very important role in daily life. But finger function recovery is quite difficult for CVD patients. One of the reasons may be that the areas of the brain that relate to the hand movement is relatively larger comparing to the areas corresponding to such as upper or lower limb movements.

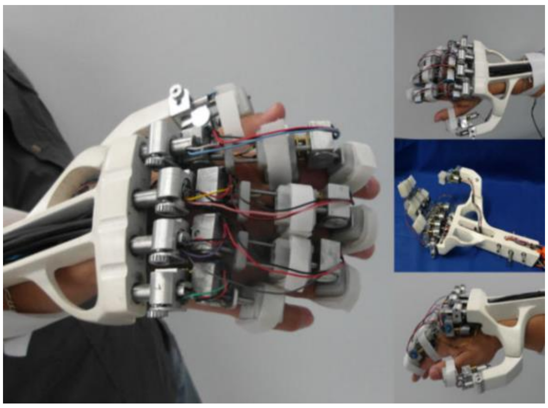

Figure 1. An example of exoskeletal finger rehabilitation device [4]

Manuscript received July 1, 2016; revised October 11, 2016.

doi: 10.18178/ijmerr.5.4.288-294

We have made a simple robotic device that will be used at home for the rehabilitation for finger function recovery [2]. Fig. 2 shows an overview of the device.

Many previous researches for robotic devices targeting at finger function recovery are consisting of exoskeletal power assist links (Fig. 1) [3]. The exoskeleton device is difficult to attach and is not suitable for home use without the help of specialists. In addition, if a patient's hand is covered by artificial objects, he/she may feel that his/her hand is not belonging to his/her own, which may bother the mental imaging of voluntary movements and causes delay of recovery.

From this point, we made our robotic device as having only simple finger lifting levers, which are assisted by a motor and equipped with pressure sensors. A patient is simply asked to lift up a finger for a while by his/her voluntary movements. If the amount of lift is insufficient, the motor supports the movement, which also helps to develop a proper association of mental image and muscular movements.

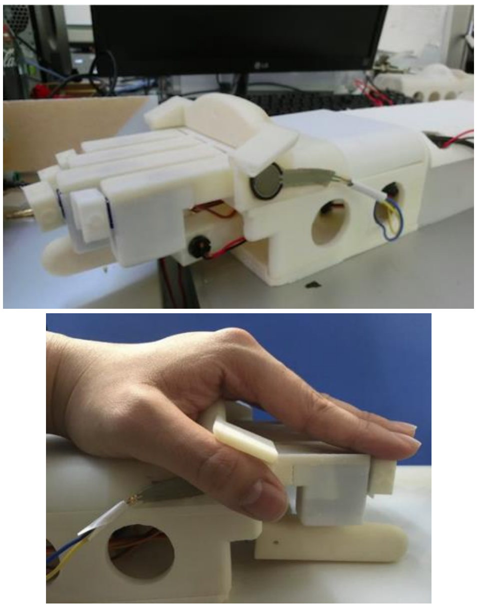

Figure 2. A finger-dedicated robotic home rehabilitation support device.

One of the essential questions for this home rehabilitation support device is whether the finger-dedicated rehabilitation is sufficient for the purpose of improving the Activities of Daily Living (ADL). Also a simple question may arise whether the limb rehabilitation at home should also be needed for the improvement of ADL or not.

In this paper, we show that the training for finger function recovery seems to affect the recovery of upper limb function. To show this, we conducted simple experiments by healthy subjects to train to produce a specified pressure on his/her finger. As the result, they had gained a skill to produce a specified pressure on his/her elbow. This means that the learning of a finger movement skill seems to result in obtaining the same skill for upper limb movement. By this, it would be insisted that the compact and inexpensive finger home rehabilitation support device is sufficient for home rehabilitation to improved ADL.

In the following sections, firstly we describe the mechanisms and the problems of finger rehabilitation. Then, we briefly show our finger rehabilitation robotic device. Finally, our experiments for skill transfer is described that will support the sufficiency of finger-dedicated rehabilitation as a target for a robotic home device.

II. Finger Rehabilitation

A. Difficulty of Finger Function Recovery

Hemiplegia caused by CVD is characterized in that the upper limb function is harder to be recovered than that of the lower limbs and there are few cases that recovery of finger function, in particular, was achieved. The reasons may include the fact that hands account for larger area in functional localization within the brain and that use frequency is higher in the lower limbs than the upper limbs even associated with paralysis [4]. It is not a rare case that hemiplegia patients walk on their own in a state called *hemiplegic gait* and ADL exercise may often shift to a practice using unaffected side of the upper limbs. Since some patients are found to have higher potential in the paralyzed hand, treatment of paralyzed hand is often overlooked for patients who adapt to daily living by using unaffected hand in many cases. Intentional motion of paralyzed hand is inhibited by a motion called as *mass flexion and extension* [5] associated with voluntary contraction which is called as *synkinesis* (*synergic movement*) of specific symptom pattern. Therefore, treatment is usually performed from the shoulder girdle to the upper arm initiating from muscles proximal to the trunk [6].

This causes the delay of finger treatment. Usually, treatment of fingers focuses mainly on holding and releasing motions by mass extension. By this, treatment of fingers tends to finish at an insufficiently early stage where a patient recover to the extent he/she can handle an object by fingers. This may lead to secondary disorders such as a phenomenon of hardening of muscle tissue called *contracture* and motor amnesia of fingers due to long period of non-use.

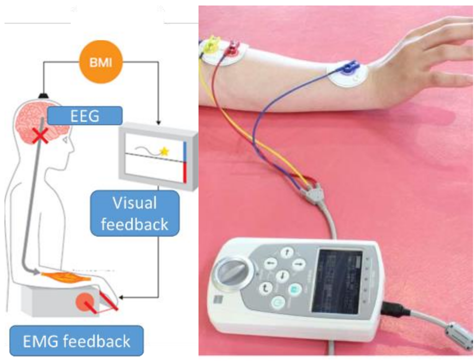

Figure 3. IVES: A BMI based hand rehabilitation device [7].

B. Problems for Finger Rehabilitation Support Devices

Currently, devices to support upper limbs of patients suffering from aftereffects of CVD, such as Brain Machine Interfaces (BMI) and Integrated Volitional

Control Electrical Stimulator (IVES), are actively developed in Japan. Most of these systems support upper limb movements by detecting voluntary muscle contractions [7], [8] (Fig. 3).

However, these devices use brain waves and other bio signals as intermediaries, which are often costly and require large spaces, making their introduction to personal rehabilitations at home very difficult.

The global trend, on the other hand, mainly focuses on the development of glove-shaped actuators and robotic arms. Because the therapeutic aim of the rehabilitation using these devices is limited to the rough movement of the upper limbs which requires a large space, they are not suitable for finger rehabilitations at home.

III. Simple Robotic Finger Rehabilitation Support for Home Use

One of the major problems of finger rehabilitation is the difficulty to properly describe the first-person feeling. In daily life, we normally have no idea of feeling the effort of moving a finger muscles by our will. However, for therapeutic purpose, it is important for a patient to be clearly aware of his/her voluntary contraction of muscles. Therefore, the rehabilitation support device currently under development in our research exclusively targets the contraction of one finger at a time, through which a patient is easily be aware of the muscle contraction.

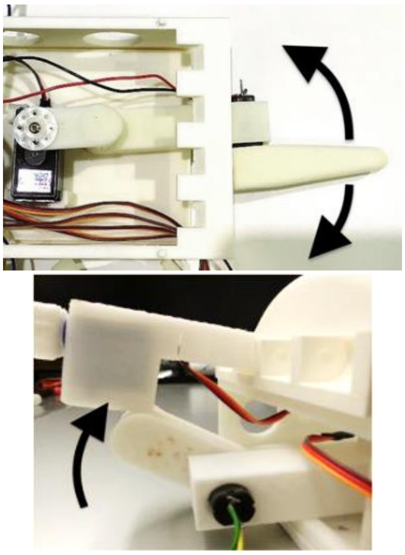

Figure 4. A finger selection and lift mechanism.

Fig. 2 shows our finger-dedicated robotic support device. A patient puts his/her hand over the device. Each finger is placed on an individual lever plate, which is selectively lifted up by a small motor (Fig. 4).

Fig. 5 shows the sequence of the finger exercise by the robot. Firstly, the patient is asked to lift his/her specific finger and keep the finger up for a few seconds (Fig. 5 right). This instruction is given by either a voice or a screen text. If the patient is not able to lift the finger, the robot will assist his/her finger lifting as in the left and the middle figure in Fig. 5. The reason of asking to keep the finger up is to encourage voluntary contraction.

During the lift exercise, pressures applied on all the fingers are simultaneously measured, which are used to determine the patient’s current recovery stage and the necessity for additional assistive power to lift.

At present, we are investigating a method to determine a patient’s degree of recovery from the information of the measured pressure values by using time series analysis or some machine learning schemes.

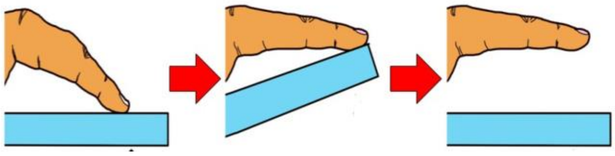

Figure 5. Sequence of finger rehabilitation with power assisted lift.

As we believe a large-scale device is not practical in terms of convenience and cost, our device is simple and easy to exchange information for both the patients and developers.

Also, based on the brain activation associated with an *active touch*, we are going to add the device with a task of giving a sensory stimulation to a fingertip to let the patient recognize the contents of the stimulation [2]. As searching movements through active touches are known to involve more joint movements, we consider it an effective stimulation for the activation of finger functions. This support system achieves economy and compactness for use at home.

IV. Appropriateness of Finger-Dedicated Rehabilitation as Home Support Device

A. Skill Transfer from Finger to Upper Limbs

As mentioned earlier in this paper, it is unknown whether a finger-dedicated rehabilitation is sufficient for the home rehabilitation purpose which aims at improving the quality of daily life (ADL). To answer the question, we conducted a series of simple experiments with healthy subjects and showed that a motor skill gained at a finger movement seems to effect on performing the same skill by an elbow movement. This result will support that the finger-dedicated rehabilitation may improve the ADL by the functional recovery for hands, fingers, and upper limbs.

B. Sense of Weight as a Skill

The sensorimotor functions of human body are complicated and mysterious. One of such functions is the *sense of weight*. Everything has a weight, so the manipulation of something means the expression of adaptive or responsive ability of finger motor functions that are used in response to the weight of the thing. Upon obtaining the visual information of the shape and size of a thing, fingers handle the thing through the memory of experience without difficulty.

The sense of weight will be acquired through some experiences or trainings such as holding an object, guessing its weight, and being told its true weight. By this, one can guess the weight of a holding object closer to its exact value. Similar training is possible by being asked to produce a specified force and then being taught its exact value of force measured by a force sensor.

Consider the situation where this training is done by using either right or left fingers. Specifically, a person is asked to push a button by a specified force, and then he/she is told the exact force which he/she was trying to produce. That person will become better to produce a specified force on his/her fingertip. This is a skill acquisition of the sense of weight.

Suppose the finger trained person is asked to produce a force at a different point of the same side of upper extremity such as an elbow. If he/she is able to better produce the specified force, it would be said that the skill of weight learned by a finger was transferred to the entire upper extremity of the same side.

If this seems to be true, it would be said that a functional recovery of fingers by the training of fingers will lead to the functional recovery of the upper extremity of the same side. This will support the sufficiency of finger dedicated rehabilitation devices for home use.

From this viewpoint, we have decided to experiment on the sense of weight. The sense to detect weight involves functions of many parts and organs. All of these functions, including muscle tension adjustment, joint movements, and senses of movements and locations, form the essential factor of finger movements. Weight can be defined as the motor sensation itself [9], but most of the motor sensations function as a passive weight detector. In this study, we have asked some healthy subjects to actively press the pressure meter. The active push provides the stimulation to the brain instead of having them passively detect the sense of weight.

C. Outline of the Experiment

Some therapists experience successful cases as a result of working on finger treatment of patients with disabilities protracted for years. This experiment requires a lot of patience, as it aims to obtain the patient's one-person feeling. Since fingers on the paralyzed side with enhanced degree of freedom become capable of intentional movement as the result, quite a few patients try to learn new motions using the upper limbs. While self-rehabilitation is recommended due to the current medical care situation in Japan with a restriction in rehabilitation as mentioned before, it is quite difficult for patients to cure on their own because rehabilitation associated with recovery of paralyzed hand function requires high-level expertise and elaborate intervention.

In order to figure out a possibility for appropriate therapeutic intervention to fingers to enhance functional recovery over the upper limbs, we have examined an appropriate sensory input as a basis of motor learning of finger function and focused on *sense of weight*, a combined sensation indispensable to accomplish the movements in ADL.

Therefore, we would like to report an experimental comparison of the way to be recognized between senses of weight fed back from fingers and the elbow part which is more proximal part.

[Subjects] 17 healthy people aged from 21 to 30 without any history of neuromuscular disease who have agreed with the participation in this experiment.

[Method] Subjects were divided into two groups; *finger-input elbow-output* group 1 and *elbow-input finger-output* group 2, in which participants press a pressure gauge by a finger and by an elbow as a motion practice to subsequently reproduce the weight by the elbow and by the finger, respectively.

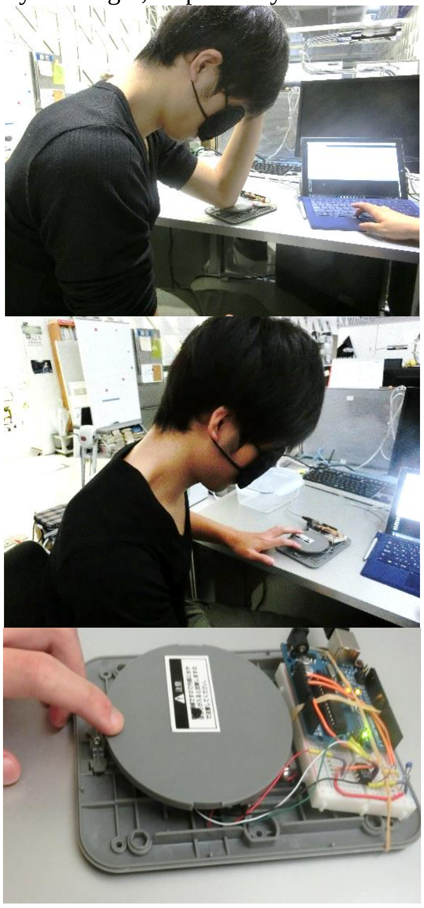

Figure 6. Measurement of the output pressure by an elbow (upper) and a finger (middle). Pressure is measured by a strain gauge connected to a PC (lower).

Figure 7. The finger position during experiments.

D. Procedure of the Experiment

Subjects were seated on a chair in a relaxed posture (Fig. 6) and a scale equipped with a strain gauge was set up (Fig. 7) to measure the pressure. Then, each subject is asked to press the pressure gauge at 0.5 kgf. Total 10 minutes were given for practice. Reproduction trial is performed 20 times and confirmation operation is permitted to perform for each trial by the corresponding effect point (either the finger or the olecranon which was used for the motion practice).

Since visual sense is blocked by a blinder during the confirmation operation, indicated values on the pressed pressure gauge were read aloud by an examiner for subjects to confirm aurally. By making subjects press the pressure gauge for five seconds continuously by the effector organ for reproduction (the elbow for group1 and a finger for group 2) for each trial, a sensor connected to the pressure gauge was set up to record the results for every 10 msec.

To prevent transitional noises, each time series of a pressure data for 3 seconds was truncated its starting and ending 1 seconds. Only intermediate 1 second data is used for the analysis.

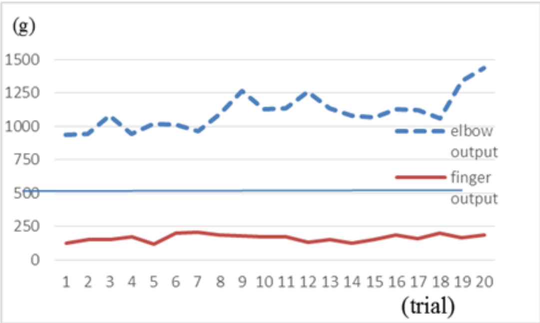

Figure 8. Transition of the mean values for each group.

TABLE I. THE AVERAGE OF THE GROUP

Trial count	Elbow output	Finger output
1	939.0	121.5
2	941.7	153.7
3	1080.9	152.1
4	940.5	169.8
5	1018.6	120.5
6	1010.6	199.7
7	962.8	208.1
8	1091.5	187.4
9	1265.0	177.1
10	1126.0	172.8
11	1134.9	171.2
12	1260.0	133.9
13	1135.8	149.6
14	1080.7	127.7
15	1067.4	153.8
16	1129.7	186.9
17	1121.4	162.0
18	1058.4	203.0
19	1342.0	162.7
20	1435.7	186.1
average	1107.1	165.0

E. Results

The actual measurement values for each group are shown in Table I. The average pressure values were 1107g for the finger-practice elbow-output group and 165g for the elbow-practice finger-output group, according to Fig. 8.

F. Discussions

A concept called *internal model* is used to express the sense of weight. It is a motor image evoked for the weight or size of an object based on visual information [10].

It is assumed that humans adopt motor programs according to visual information obtained from an object based on this internal model, as well as past experiences, and manipulate objects used in daily life [10]. However, we performed reproduction of sense of weight without visual information in our experiment, thus the subjects might have applied an instantly-produced model comprising information fed back directly from body parts. This sense of weight is a sense that cannot be simply verbalized, and can only be known based on first-person descriptions and physical data measured.

The difficulty in expressing “weight without a physical object” by body is comparable to the difficulty in explaining why humans can raise their arms or can walk. These are profound problems that a rehabilitation therapist encounters without exception. If the therapist cannot consider these phenomena, the rehabilitation is quite likely to be an intervention in which the patient only imitates according to verbal instructions or is only forced into passive exercises. Such an intervention is far from an effective treatment maximally utilizing appropriate feedback.

In this experiment, results measured for two organs, the finger and the elbow, between which large differences in muscle mass, distribution of skin receptors, constructive structures and thresholds of deep sensation and so on exist, are compared.

There are large differences in the force necessary to perform the task of 0.5 kgf pressure between the finger and the elbow. Whether this sense of 0.5 kgf tactile pressure is strong or weak for the finger is the first problem to discuss. In the preliminary experiment, we examined the double-fold force, 1 kg. However, it became clear that it was more difficult a task for the subjects to press the pressure gauge at 1kg with the finger continuously than to press with the elbow. Therefore, we set the executable force as 0.5kg, which the subjects can press continuously.

Another discussion is the appropriateness of the 0.5kgf for the sensitivity range of humans. The sense of 0.5kgf weight is not usually experienced in daily life. Therefore, the task of producing exactly 0.5kgf is a new experience for most of humans which has never been learned. We expect that linking sense with motor expression, which is rarely experienced in the daily life, will generate a new program in the brain or the internal model.

From the data, there were large differences in the actual output between 2 groups (finger-input elbow-output and elbow-input finger-output), whereas the value of the instructed force was the same (0.5kgf). This indicates that for skin receptor organs, humans have lower threshold of tactile pressure sensitivity on the fingertip than on the elbow. The threshold of tactile sensitivity is expressed by the given stimulus, force (g/mm^2), displacement of the skin (μm), the velocity of skin pressure (mm/s), and so on. It is known that the threshold of sense points is low on a fingertip, which ranges approximately from 0.3 to 0.5 g/mm2, whereas threshold on an arm is 10 to 30 times higher [11]. By this fact, the subjects seemed to feel elbow inputs weaker than finger inputs.

From structural point of view, the fingers and the elbows are largely different from the size of the joints and muscle mass. The elbow-practice finger-output group can be considered as a *suppression model*, in which the weight of the elbow (equals to the shoulder joint) was strongly suppressed, and the finger-practice elbow-input group can be considered as a *facilitation model*, in which strong facilitation was performed to small muscle mass.

The subjects' descriptions are also notable. The subjects who pressed the pressure gauge with the finger and then taught the measured pressure described that 0.5 kgf was quite a strong output for the finger and they had to use very large force, therefore they reproduced the force also by the elbow. The subjects who experienced 0.5 kgf force with the elbow and reproduced it by the finger described that they felt small force when they experienced 0.5 kgf with the elbow, therefore they reproduced it correspondingly. This means that, in imaging the input of the stimuli, experiences with the finger had stronger impact on the brain than experiences with the elbow.

From these facts, it is likely that the differences in the measurements was not just the differences in muscle mass or the weight of the finger and the elbow, but the differences in the traits of personal images or promptly-produced internal models. In addition, it has been suggested that the traits of an internal model strongly depend on the quality and quantity of sensory input that fed back.

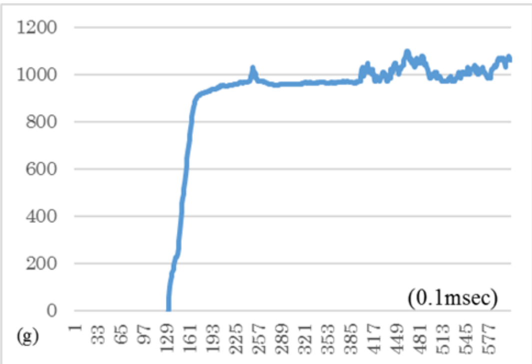

Figure 9. Transition of pressure output by elbow of one subject.

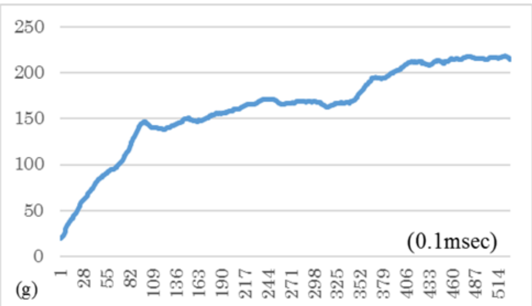

Figure 10. Transition of pressure output by finger of one subject.

Comparisons of a time series for a typical subject show some tendencies (Fig. 9 and Fig. 10). With the elbow, the output from 0 kgf linearly exceeds the reference value of 0.5 kgf and reaches at its peak. In contrast, the finger output steadily approaches the peak value on a curve. This may be the result by the weak impression due to the weak brain application during the elbow practice. However, the curve describes the tendency to express the carefully imaged sense of weight.

In summary, it was suggested that in interventions for motor function recovery in post-stroke hemiplegia patients who have degreased muscle output and are controlled by synkinesis (synergic) movement pattern, feedback from the fingers with low sensitivity thresholds, i.e. feedback of joint sense by introduction of specific joint movement and strong tactile pressure from the skin need to be stressed and utilized to build appropriate internal models.

V. Conclusions

A finger-dedicated robotic rehabilitation support device has been introduced that is compact enough to be used at home. The device is intended to induce voluntary muscular contraction at a finger by the help of a simple power assisted finger lifter. For the question of whether finger targeted robotic rehabilitation at home is sufficient to improve the quality of life, we have shown some results of the experiments that describes the transfer of learned motor skill from a finger to an elbow.

Although the conditions and variations for the experiments are not sufficient yet, the results would demonstrate that the finger-dedicated robotic rehabilitation support device would be effective not only for finger functional recovery but also for the recovery of upper limb functionality. Therefore, a compact finger support device would be a good candidate for home rehabilitation system that aims at improving the quality of daily life.

Acknowledgment

The authors would like to thank the staffs of the Takikawa Neurosurgical Hospital for their advices and help with the development of this robotic device.

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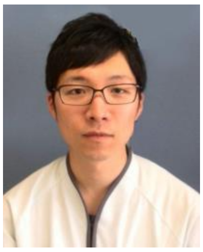

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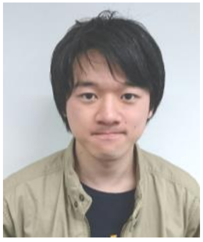

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