Development of Exo-Finger for Grasp-Assistance

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Abstract—The most common outcome of stroke is hemiplegia and it is known that finger paralysis in particular tends to remain. These patients feel inconvenient in daily life because the grasping operation becomes difficult. On the other hand, not moving the paralyzed fingers for a long term will cause joint contracture. Therefore, daily use of the paralyzed finger is important to prevent joint contracture. To solve these problems, we propose applying a wearable assistive system that provides grasp-assistance for finger paralysis patients. The purpose of this research is to develop the "Exo-Finger" for grasp-assistance. The Exo-Finger is an exoskeleton system that assists the cylindrical grip that often appears during daily life. A wire is connected on the end point of the frame. When the motor pulls it, it is possible to extend the MP (Metacarpophalangeal), PIP (Proximal interphalangeal), and DIP (Distal interphalangeal) joints together. Elastics are used to assist flexion of the fingers. Moreover, we developed two kinds of control interfaces based on the state of the paralyzed finger. One is using a push switch operated by the healthy hand and another is using the small movement of the finger as a trigger. Through the experiment with a hand mock-up, grasping operation could be achieved as grasp-assistance with Exo-Finger. In conclusion, we developed the Exo-Finger and confirmed that the Exo-Finger would be used for grasp-assistance in daily life.

I. INTRODUCTION

Stoke is a serious brain disease. In Japan, several hundred thousand people develop stroke every year [1]. Stroke causes various aftereffects, and the most common is Hemiplegia. It is a motor dysfunction that makes patients unable to move the right or left side of their body. The condition of hemiplegia depends on the rehabilitation and level of brain injury. Especially, the part of the motor cortex responsible for finger movements tends to be damaged by stroke. It is known that finger dysfunction tends to remain. Moreover, the number of patients who can receive sufficient rehabilitation is restricted because of the restrictions of the rehabilitation period and shortage of therapists. Therefore, most hemiplegia patients live daily life with paralyzed fingers.

Once paralysis occurs in fingers, it becomes difficult for the patients to grasp an object. The grasping operation appears in all scenes of daily life. Thus, the loss of grasping function makes patients’ daily life inconvenient. And it causes decrease of Activities of Daily Living (ADL) and Quality of Life (QOL).

Meanwhile, when the patients don’t move their paralyzed finger for a long term, it causes joint contracture. It causes limitation of the range of joint motion, and it becomes an obstacle of daily life and rehabilitation. In order to prevent joint contracture, it is effective to use the paralyzed finger in daily life or to move it by external force. However, it is difficult for finger dysfunction patients to use the paralyzed finger. Additionally, when the joint contracture occurs, it becomes more difficult to use the paralyzed finger, and results in worsening of the joint contracture. Therefore, in order to prevent joint contracture, it is important to move the paralyzed finger by external force.

In short, the requirements for the patients are summarized as follows;

1) Assisting the grasping operation of patients
2) Moving paralysis finger to prevent joint contracture

These two things are important for finger paralysis patients. In order to actualize the requirements, we are focusing on a wearable assistive system to provide grasp-assistance for the paralyzed finger. By using a wearable assistive system, it is expected that increase of ADL and QOL by grasp-assistance and prevention of the joint contracture by daily use of the paralyzed finger. Additionally, daily use of the paralyzed finger promotes the neurorehabilitation [2]-[5] and there is a possibility that the paralysis improves.

For these patients, two types of assistive systems have been developed. First, Engen plastic hand orthosis [6] is a functional orthosis to assist grasping. This orthosis enables grasp-assistance by converting the wrist motion into the motion of the MP joint through a link rod. It is a lightweight orthosis because it doesn’t require power such as an electrical motor. However, it is impossible to apply it for patients who cannot move their wrist, and the application is limited. Second, wearable type grasp-assistance systems using power sources...
such as electric motors and pneumatic actuators have been developed [7]-10. This system has possibility to use for the patients who cannot move their wrist. However most of those systems can assist only index and middle finger and the PIP and DIP joints are fixed. From the viewpoint of the prevention the joint contracture, it is important that the patient moves all his fingers on the paralyzed side [2]. Therefore, the wearable system that provides grasp-assistance for multiple fingers is required.

The purpose of this research is to develop the "Exo-Finger" for grasp-assistance of finger paralysis patients. In this paper, we develop the hardware and the interface of the Exo-Finger and confirm the effectiveness of grasp-assistance by an experiment with a hand mock-up.

II. DESIGN OF EXO-FINGER

A. Target Patients

Brunnstrom Stage [11] is an evaluation method that stages the recovery of the motor function after stroke. This method is widely used to evaluate motor function of hemiplegia patients in Japanese hospitals. Brunnstrom Stage concerning finger motor dysfunction is as follows.

**Stage1**: Flaccidity
**Stage2**: Little or no active finger flexion
**Stage3**: Mass grasp, use of hook grasp but no release, no voluntary finger extension
**Stage4**: Lateral prehension, semivoluntary finger extension, with small range
**Stage5**: A variety of grasping operation awkwardly performed and with limited functional use, voluntary mass extension with variable range
**Stage6**: All prehensile types under control, full-range voluntary extension, individual finger movements present but less accurate.

After stroke, the condition of the paralyzed finger is stage 1 or stage 2. These patients cannot move their finger voluntarily at all. Many hemiplegia patients recover up to Stage 3 or Stage 4 by rehabilitation. However, the number of patients who recover up to stage 5 and stage 6 that can voluntarily extend their finger is limited. And in most cases, their recoveries stay in stage 3 and stage 4, and the paralyzed finger remains flexed. These patients can flex their finger voluntarily, but they cannot extend their fingers to grasp or release an object. As a result, the patients cannot grasp the object well. If the patient at Stage 3 and Stage 4 extends his finger by the external force, it is expected that the patients are able to grasp an object by their residual function. On the other hand, patients at Stage 1 and Stage 2 cannot move their finger. For these patients, it is possible to assist extension and flexion of the paralyzed finger with wearable system in order to prevent joint contracture. Patients at Stage 5 and Stage 6 are already able to perform the grasping operation. Their problems are to improve the dexterity of their fingers. Therefore we targeted patients in Stage1-4.
B. Target Operation

It is important that the patient uses all his fingers on the paralyzed side in order to prevent joint contracture. However, if the wearable system assists the motion of all fingers, the hardware of the system will become complicated and heavy. In this research, we selected a cylindrical grip (Fig.1) as the assistance operation to realize a simple and lightweight hardware. The cylindrical grip is a kind of grasping form that often appears in daily life [12]. In this grasping form, the four fingers (Index, middle, ring, and little finger) wrap the object while thumb is fixed. It is possible to move each joint of the four fingers by assisting cylindrical grip with the Exo-Finger. The grasp-assistance is indirectly performed by assisting extension of the four fingers as described in the foregoing paragraph.

C. Required Specifications

Exo-Finger is a wearable system that promotes daily use of the paralyzed finger by providing grasp-assistance. Therefore, it is required not only to perform grasp-assistance but also to wear the system without user's load. The following are listed as requirements of the Exo-Finger.

1) Compact size and lightweight to be potable
2) Control interface corresponding to user's condition
3) Obtain enough range of motion
4) Assist paralyzed finger, and enable grasping

The system of the Exo-Finger consists of the hardware (Hand unit), the interface and the control unit as shown in Fig.2. In this research, we develop a hardware and an interface that satisfy 1), 2). Next, it is verified that the hardware satisfies 3), 4) in an experiment with a hand mock-up.

D. Hardware

Figure.3 shows the main body of the Exo-Finger. It has the exoskeleton structure and the rotation axis in MP, PIP, and the DIP joint on the index finger side. And the thumb is fixed opposite to other fingers by the exoskeleton. The bridges are installed in the backside of the finger, and the frame on the forefinger side transmits power to the four finger through the bridge. The mechanical limiter is installed in the frame to avoid hyperextension for safety. An electric motor is installed on the back of the hand of the exoskeleton. Moreover, potentiometers are installed into MP, PIP, and the DIP joint on the index finger side, and it is possible to measure the joint angle. Velcro and rubber bands are used to attach the exoskeleton to the hand, it realizes the easy wearing. The finger frame is made of aluminum alloy, which has enough strength and lightness. The weight of the main body is about 230g. It is light enough compared with about 280g for the electric flexor hinge splint [7].

The appearance of wearing the whole system is shown in Fig.4. The control system can record, and monitor sensor information. A control box and a battery box are packaged individually. These can be installed in the user's belt with a hook. The user can move wearing the whole system.

The grasp-assistance mechanism is shown in Fig.5. In order
to realize a simple mechanism, the tendon drive with wire and elastic is adopted. The Exo-Finger assists the movement of each joint considering that the joint axis of the four fingers is about the same. The wire is connected on the end point of the frame. When the motor pulls the wire, the Exo-Finger extends the MP, PIP, and DIP joints together by a single degree of freedom. The elastics are used for assisting flexion, so it is possible to assist the grip force passively. By changing the strength of the elastic, it is possible to adjust the assisting grip force according to the grip force of the patients. Moreover, the finger fits the object and the motor does not have to keep outputting power during grasping of the object.

E. Interface

It is required that the system has an interface based on the condition of the patients in order to promote daily use of the paralyzed finger. The Exo-Finger can be used for various patients by using adequate interfaces. In this research, we develop two basic interfaces based on BrunnstromStage for the evaluation of the Exo-Finger. Each interface is explained below.

Case1: BrunnstromStage1-3

Patients at BrunnstromStage1 to Stage3 cannot voluntarily extend their finger at all. For these patients, we prepared an interface with a small push switch (Fig.6). The user operates it using the healthy hand. It is a simple control method that switches the extension and the flexion with the push switch. The extension begins when the switch is pushed, and stops when the angle sensor detects reaching the limit of extension. When the switch is pushed again, the flexion begins. The finger comes in contact with the object during flexion, and the time, which the angle rate for each joint becomes 0, is judged as grasping the object, and operation stops. As a result, the Exo-Finger can grasp to fit the object. It is possible to control it without holding it, because the switch can be installed on the control box. In addition, this interface also can be used when the patient voluntarily exercises the finger in the early stage of rehabilitation.

Case2: BrunnstromStage4

It is important for patients to use the patient’s residual function as much as possible to prevent contracture. The patients at BrunnstromStage4 can voluntarily extend their finger a little. Therefore, we developed a control method using little extension of the finger as a trigger. The angles of the joints are shown in Fig.7, and the graph of the movement-trigger operation is shown in Fig.8. We use the angle rate of the PIP joint as a trigger. When the set threshold is exceeded, then the finger begins to extend. The extension of the finger is assumed to be the preliminary operation the grasping an object, and after the extension, flexion begins automatically after a set time. During flexion, the control method is same as in case1.
III. EXPERIMENTS & RESULTS

We confirmed the range of motion (ROM) and effectiveness of the grasp-assistance as a fundamental experiment before applying the Exo-Finger to hemiplegia patients. We performed the experiments with a hand mock-up. The mock-up contains a frame shown in Fig.9. It is covered with sponge and contains three free joints in each finger. We performed the experiments by actual installing Exo-Finger to the mock-up. The push switch interface was used in the experiment for the control.

A. Range of Motion

First, we evaluated the joint's ROM with the mock-up. The graph of the operation is shown in Fig.10 and table.1 shows the ROM compared with human ROM. The flexion of the fingers is limited by the finger pulps, but it is enough to grasp the object. It is possible to perform the flexion and extension of a finger within one second. Moreover, The Exo-finger did not slip out from the mock-up while operating. Thus, it was confirmed that the Exo-Finger fits firmly on the mock-up.

B. Grasping Objects

To confirm the effectiveness of the grasp-assistance mechanism, we performed an experiment by actually grasping an object. A PET bottle and a spoon, which are often used in daily life, were selected as the grasping objects. The diameter of the PET bottle is 65mm, and weight is about 500g with water. The spoon was assumed to be a self-help device, and the axis diameter of 30mm was used. If the mock-up can grasp the objects with the Exo-finger, the hemiplegia patients would be able to grasp the objects because the remaining grip force of the patients is added to the Exo-Finger force output.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>RANGE OF MOTION</th>
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<tbody>
<tr>
<td></td>
<td>DIP ROM (deg)</td>
</tr>
<tr>
<td>Human finger</td>
<td>0 – 80</td>
</tr>
<tr>
<td>With mock-up</td>
<td>0 – 80</td>
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Fig.11 shows the images and the graphs of the experiment. The graph shows that it is possible to grasp fitting to the different size objects. Moreover the mock-up could grasp the bottle by passive assistance of the Exo-Finger. It would be possible to provide grasp-assistance by the Exo-Finger for the patients with low grip.

IV. CONCLUSION

In this research, we developed the Exo-Finger to realize grasp-assistance for hemiplegia patients. Exo-Finger is a lightweight system, and it enables to assist motion of each joint from index finger to small finger. Moreover, to evaluate the operation of the Exo-finger, we developed two kinds of basic control interfaces based on BrunnstromStage. It would be possible to expand the application of the Exo-Finger by using various interfaces based on condition of the patients. In the experiment with a hand mock-up, grasping a bottle and a spoon could be achieved as grasp-assistance with the Exo-Finger. We confirmed that the Exo-Finger would be able to use for grasp-assistance in daily life. As the next step, we plan to apply the Exo-Finger to grasp-assistance in daily life and rehabilitation.

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REFERENCES

[1] Ministry of Health, statistics patient survey for 2005, Table 12 The total number of patients with major injuries