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Development of Hand-Assistance Device using Hand-Joint Orthosis and Neuromuscular Electrical Stimulation

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Abstract— **The development of self-help devices has attracted attention in the light of improving the activities of daily living (ADL) in patients with finger paralysis. These devices are required to reduce discomfort and enable greater degrees of grasping motions in patients. In this study, we developed a lightweight self-help device that uses neuromuscular electrical stimulation and hand-joint orthosis to finely control the fingers. In addition, we examined the possible grasping actions by testing how well the users of this device exhibited improvements in their ADL. Our results indicate that our self-help device can potentially be adapted to address finger paralysis.**

***Clinical Relevance*: With this device, paralytic of finger can have an improved quality of life in terms of their ADL.**

I. INTRODUCTION

Patients with finger paralysis find it difficult to grasp objects. Consequently, they perform poorly with regard to activities of daily living (ADL) and often require the care and support of others. These days, self-help devices are used as tools to assist such patients toward leading an independent life. Current commercially available self-help devices can significantly improve ADL; however, many are customized for specific movements and do not allow multiple grasping movements. Some versatile self-help devices for paralyzed hands are too heavy, while others afford fewer possible grasping motions than satisfactory. Moreover, there are no self-help devices that can be worn on a daily basis to perform various types of grasping motions. Here, we demonstrate a self-help device that can be worn without difficulty while supporting various types of grasping motions [1] [2]. Specifically, we develop a system that uses hand-joint orthosis and muscle contraction through surface electrical stimulation and verify its applicability.

II. SELF-HELP DEVICE USING HAND-JOINT ORTHOSIS AND NEUROMUSCULAR ELECTRICAL STIMULATION

Our design considered the following design requirements for self-help devices:

- The device must be sufficiently small to avoid interference with ADL.
- The device must be portable and lightweight to ease user comfort on a daily basis.
- Users must be able to perform a variety of grasping motions, including power grasp, tripod pinch, lateral pinch, and open palm.

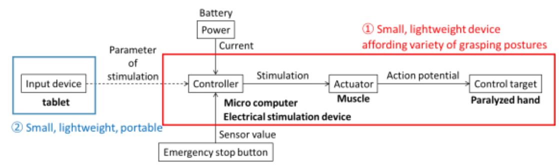

Figure 1. Schematic of complete self-help-device system.

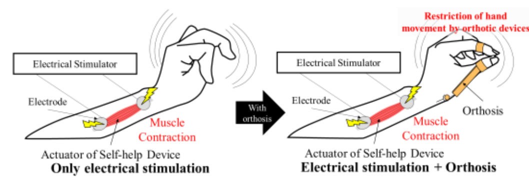

Figure 2. Schematic views of conventional and proposed systems.

Figure **1** shows a system that meets the previously mentioned requirements. To obtain compactness, light weight, and portability, we use a system that wirelessly communicates between the input device and the controller. Furthermore, to meet the requirements of compactness, light weight, and affordability of various grasping motions, we use hand-joint orthosis together with neuromuscular electrical stimulation (Figure **2**). Here, a pair of electrodes is attached to the skin surface, which covers the muscle fiber to be stimulated, and muscle contraction is caused by this electrical stimulation, thus allowing the fingers to move. At this point, the patient's own muscle becomes the actuator of the self-help device, and no mechanical actuator (for e.g., compressor or motor) is required. This setup largely solves the two major problems of device size and weight. However, it is difficult to detect the target muscle and stimulate only this location because the electrical stimulation occurs at the skin surface. Moreover, it is difficult to control the fingertip position. Therefore, we restrict the fingertip position by attaching a hand-joint orthosis to the fingers and controlling their movement. In this study, we particularly consider restricting finger movement to facilitate the tripod pinch, which requires a high degree of control of the fingertip position.

A. Surface electrical stimulation

1) Stimulation of the target muscle

The finger movements necessary to performing grasping motions in ADL include the opposing movements of the thumb, flexion of the index and middle fingers, and extension of all fingers. To realize these three actions from muscle contraction caused by electrical stimulation, the following muscles were stimulated (Figure **3**):

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- opposite the thumb, i.e., thenar muscles (TM);
- flexion of the index and middle fingers, i.e., flexor digitorum superficialis (FDS) muscle;
- extension of fingers, i.e., extensor digitorum muscle (EDL).

2) Stimulus waveform

To suppress the sensation of pain, we used a stimulation waveform obtained by burst-modulating a biphasic high-frequency pulse.

3) Control method

To realize the grasping postures necessary for ADL, we varied and controlled the order of electrical stimulation provided to the three muscles to be stimulated. Here, we note that the tripod-pinch posture can be achieved by the flexion of the index and middle fingers in a state in which the thumb is first in opposition. A lateral pinch is achieved when the thumb is in opposition, with the index and middle fingers flexing first. The open palm is realized when the fingers are extended. The order of the applied electrical stimulus corresponding to these three postures as well as the state in which the electrical stimulus is removed are defined as follows: tripod pinch, TM → FDS; lateral pinch, FDS → TM; open palm, EDL; off, electrical stimulation removed.

In our setup, electrical surface stimulation is applied to the target muscle by pressing the four buttons corresponding to the above actions on a tablet (the input device), resulting in muscle contraction and the desired grasping posture. In the study, parameters such as frequency and voltage were adjusted for each participant, and grasping postures were controlled only by turning the stimulus on and off.

B. Hand-joint orthosis

1) Thumb orthosis

The mechanism map of the thumb orthosis is shown in Figure 4(a). When electrical stimulation is applied to the TM, undesired movements of the thumb, including the flexion of the metacarpophalangeal (MP) joint and adduction can occur in a state in which the thumb is opposite to the four fingers. To prevent this reaction, a link mechanism such as a splint from the carpometacarpal (CM) joint to the MP joint is used. Instead of fixing the thumb in an opposing state by connecting the wrist position of the splint with a ball joint, we can apply an opposing movement of the thumb while maintaining a constant opening angle of the MP joint. Consequently, although adduction can be achieved in a parallel state, the adduction and flexion of the MP joint in the opposing state are restricted. Furthermore, in our setup, the rubber elastic body was arranged such that the thumb was maintained parallel when no stimulation was applied.

2) Index- and middle-finger orthosis

The mechanism map of the index- and middle-finger orthosis is shown in Figure 4(b). When electrical stimulation is applied to the FDS, the thumb may move between the index and middle fingers, causing a “middle crack.” Therefore, the metacarpal bones of the index and middle fingers are constrained to interlock. This design restrains the abduction and links the movement of the two fingers.

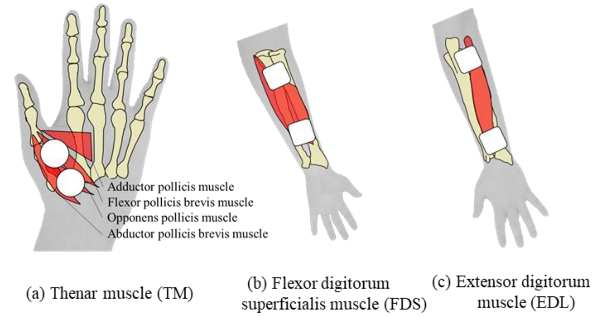

Figure 3. Stimulation of target muscles.

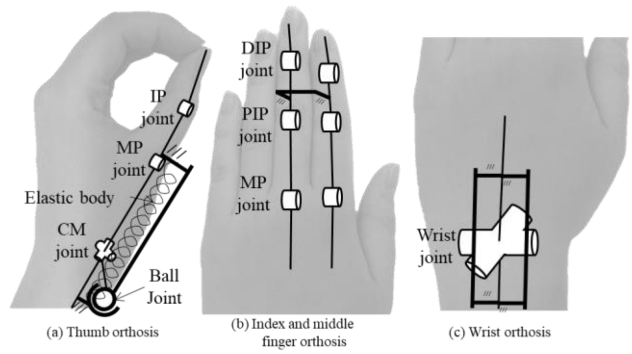

Figure 4. Mechanism of orthosis.

3) Wrist orthosis

The mechanism schematic of the wrist orthosis is shown in Figure 4(c). The wearing of a wrist supporter prevents excessive movement from electrical stimulation, such as palmar flexion or dorsiflexion. In the study, plates were placed on the palm and dorsal sides of the wrist supporter, thereby restricting palmar flexion and dorsiflexion.

III. Basic Performance of Self-Help Device

A. Mounting the developed self-help device

Figure 5 shows the photographs of the developed system and an enlarged view of the orthosis. The splint was molded using a 3D printer with acrylonitrile butadiene styrene resin. Synthetic leather was used for the index- and middle-finger braces and the fixation part of the middle phalanx of the thumb. The leather allowed the application of a total of three sets of surface electrode pads to the TM for thumb opposition, FDS for flexion of the index and middle fingers, EDL for finger extension, and further enable the application of surface electrical stimulation to achieve the desired grasping posture.

B. Basic performance

The device weight was measured to verify whether the developed self-help device was sufficiently light for daily use. The mounting weight was 63 g, the controller weight was 620 g (the weight of the electrical stimulation device = 347 g, and the weight of the tablet = 273 g). The mounting weight was equivalent to the 200 g weight of a heavy wristwatch, which is a design requirement. The weight of the portable controller was assumed to be 1 kg, which was sufficiently smaller than the design value.

We first verified whether it was possible to achieve a tripod-pinch posture close to the ideal one by wearing the orthosis. Figure 6 shows the state when electrical stimulation for the tripod pinch is applied in cases (a) when the orthosis is not worn, and (b) when the orthosis is worn. It is clear that the fingertips fit together, and the tripod-pinch posture is satisfactorily achieved upon wearing the developed orthosis.

Furthermore, we verified the accuracy of achieving the tripod pinch to ensure longevity of device use to realize this posture. The evaluation was based on the number of successes when attempting to grip an eraser and a pencil cap 10 times. The participants were five healthy males whose fingers were completely relaxed. Electrical stimulation was controlled by pressing the button of the tripod pinch with healthy hands. TABLE I lists the number of successes over 10 trials. There were some failures for both gripped objects, although they occurred owing to the patients' approach to the object, and not because of failure resulting from the fingertips not fitting. Therefore, we concluded that any participant wearing the device can achieve the gripping posture of the tripod pinch.

Next, we measured whether the developed self-help device could express the power necessary for ADL. The tripod-pinch and lateral-pinch forces, which are important for ADL, were measured. The tripod-pinch force is one of the grasping forces required to "pinch" small objects when the thumb is in a state of opposition and the index and middle fingers are in flexion. On the other hand, lateral-pinch forces are required to grasp "thin" objects such as keys and cards with the ball of the thumb and the deflection side of the index finger. It has been reported that ADL can be performed satisfactorily if a tripod-pinch force of 10 N and a lateral-pinch force of 11 N can be realized [3] [4]. In the study, we conducted an experiment to determine if this requirement was fulfilled. The participant in this case was a healthy woman, and she completely relaxed her arm to approach a paralyzed patient. We note here that tripod-pinch forces do not depend on the voltage applied to the TM, but are affected by the voltage applied to the FDS. This force was measured when the voltage applied to the FDS was varied as 8.4, 9.1, 10.1, 11.0, and 12.0 V. Meanwhile, lateral-pinch forces do not depend on the voltage applied to the FDS, but are related to the voltage applied to the TM. The set-voltage range was varied from the value at which the finger movement was expressed to the value immediately before the participant expressed pain caused by the electrical stimulation, and this measurement was performed at intervals of about ~1 V. The measurement was performed 10 times for each voltage, and the average value was obtained. The results of these experiments are shown in Figure 7. Here, the horizontal axis represents the voltage applied to the FDS for the tripod pinch and the TM for the lateral pinch, and the vertical axis represents the corresponding force. From the results, we note that the tripod-pinch force is 11.2 N when the voltage applied to the FDS is 9.1 V, and the lateral-pinch force is 11.7 N when the voltage applied to the TM is 10.1 V. Thus, our device allows the exertion of the effective power required for ADL.

IV. EVALUATION

We evaluated whether the developed self-help device could improve the level of ADL by testing the device for the following requirements:

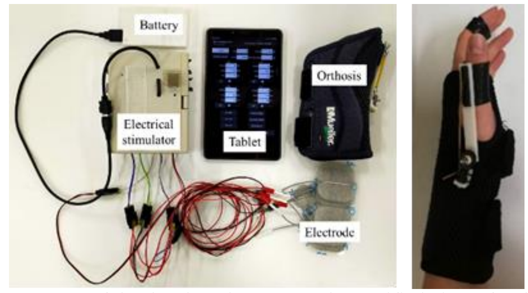

Figure 5. Images of the developed system and magnified view of orthosis.

(a) Electrical stimulation only   (b) Developed self-helped device

Figure 6. Comparison of tripod-pinch posture between electrical-stimulation-only system and our device.

TABLE I. Number of successes for tripod pinch

Subject	A	B	C	D	E
Eraser	10	10	10	9	10
Pencil cap	9	9	10	10	10

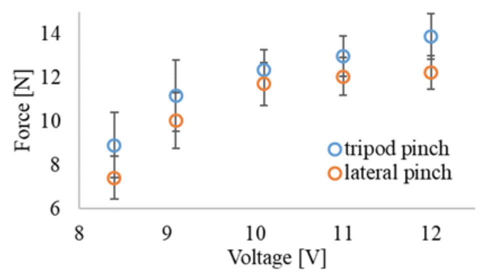

Figure 7. Expressible force at each voltage.

TABLE II. Voltage for electrical stimulation [V]

Subject	A	B	C	D	E
TM	12.0	10.0	10.0	12.0	12.0
FDS	5.5	7.0	8.0	5.0	7.7
EDL	6.0	6.5	6.5	6.0	7.0

A) Possible grasping posture
B) Shoelace-tying task

A. Possible grasping posture

We verified whether the paralyzed hand could assume the necessary posture as a hand to assist the dominant hand.

We evaluated the self-help device based on the nine postures that a paralyzed hand must be able to maintain for use as an assistive hand. These nine postures are among the classifications of grasping postures in daily living [5]. We examined the efficiency of our device when grasping various objects: fan, hammer, baseball, rag, cylinder, keys, spoon, bowl, and saucer. The participants were five healthy males. The parameters of electrical stimulation given to each participant were as follows: carrier frequency = 2000 [Hz], burst frequency = 100 [Hz], duty ratio = 70 [%], with the voltages being listed in TABLE **II**. Before the start of the experiment, the voltage was adjusted so as not to cause pain. We note here that this experiment was carried out with healthy participants, and although participants experienced a sense of discomfort due to the stimulation, there was no reported discomfort due to pain. To accurately replicate the condition of paralyzed patients, each participant's arm attached to the self-help device was completely relaxed, and the eyes of the participants were closed. The experimenter held the participant's arm and manipulated the electrical stimulation while changing the position and orientation of the hand to allow the participant to grasp the object. After grasping the object, the experimenter lifted the participant's arm until the grasped object was removed from the desk and confirmed whether the object could be grasped without dropping. Figure **8** shows the grasping state for all nine objects; it is clearly they all can be grasped. We also note that the device makes it possible to grasp all the objects mentioned in the examples necessary for the daily use of the paralyzed hand as an assistive aid.

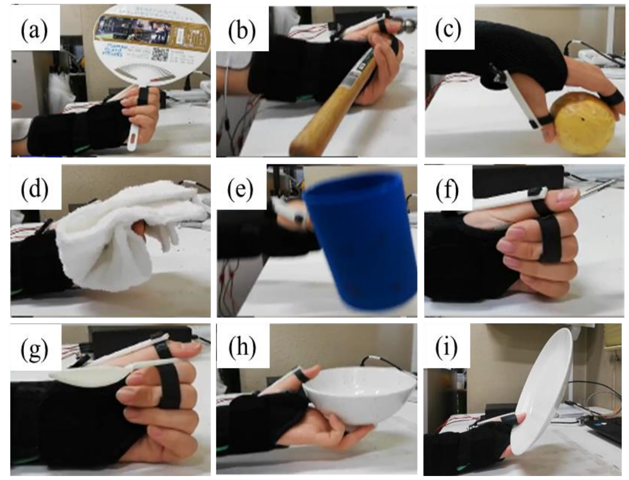

Figure 8. Variety of grasping postures with various objects.
(a) Fan, (b) hammer, (c) baseball, (d) rag, (e) cylinder, (f) key, (g) spoon, (h) bowl, (i) saucer.

B. Shoelace-tying task

A shoelace-tying task was performed to verify whether ADL could be performed smoothly by wearing the developed self-help device. We chose shoelace tying as a representative of ADL using both hands, which is difficult for patients with one hand paralyzed. In the developed system, the control input was a button on the tablet, which is not suitable for two-handed operation. Assuming the future development of a system that can operate electrical stimulation at will, this experiment in the study was conducted using a foot switch as the control input. The participants were two healthy men and women, and to verify the effectiveness of the developed self-help device and wrist orthosis, the task of tying shoelaces was conducted in three ways: wearing the developed self-help device, providing only a surface electrical stimulation, and removing the orthosis and surface electrical stimulation, thereby replicating a paralytic state. Figure **9** shows the average time required to complete the task under each condition. From the results, we find that the time required to perform the task with the self-help device is shorter than for the other two conditions. Moreover, a significant difference ($p < 0.0167$) is observed in the case of participant A, but no significant difference is found in the case of participant B. This result can be attributed to the fact that the foot switch is not an intuitive operation, and there was no significant difference in the case of participant B based on skill level. Therefore, we can conclude that the developed self-help device is effective for accomplishing the task smoothly. However, it is necessary to further develop the control method.

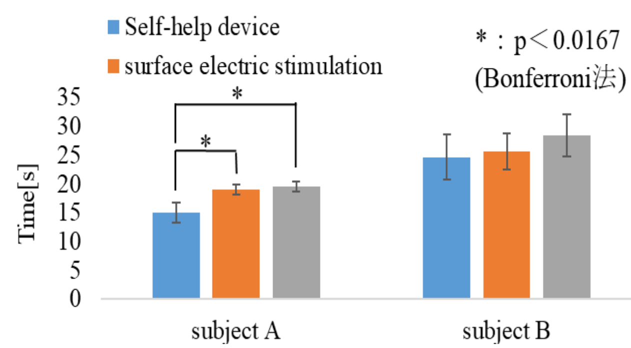

Figure 9. Time required to accomplish shoelace-tying task.

V. Conclusion

In this study, we developed a self-help device that can be worn on a daily basis and can support various types of grasping motions. Moreover, we verified whether the paralyzed hand (with the application of this device) can be used as an assistive aid for daily living. We confirmed that the device facilitates various types of grasping movements, thereby demonstrating the possibility of its adaptation to finger-paralysis patients.

In future studies, we plan to increase the number of participants, verify the device effectiveness with paralyzed patients, and review our results. In addition, we plan to focus on the voluntary control of surface electrical stimulation.

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