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Lightweight 10-DOF Robotic Hand With Built-In Wire-Driven Mechanism

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***Abstract*—The purpose of EMG prosthetic hands is to compensate for the lost functions of hand amputees. To restore the ability to perform activities in daily life, prosthetic hands need to have as many a degrees of freedom (DOFs) as possible. Furthermore, this requirement must be realized while retaining grasping stability and keeping the hand light in weight and small in size. In this study, our aim is to develop a 10-DOF hand that can form the seven finger postures that are required for daily life activities. To achieve this objective, we propose a wire-driven mechanism built over a finger skeleton and implemented it on a hand. We confirm that the developed hand can achieve all of the goal actions. In addition, our developed hand was evaluated using two indices, rate of controllability and rate of weight, as defined in this research.**

***Index Terms*—EMG prosthetic hand, DOF, wire-driven mechanism**

I. INTRODUCTION

The hand of a human is an excellent manipulator and an advanced communication tool. Therefore, it is difficult for a person who loses his or her hands to manage the activities of daily life. According to [1], there were about 1.81 million patients with physical disabilities in Japan in 2013, and about 80 thousand of them had lost their upper limbs. EMG prosthetic hands are one way to compensate for lost hand functions, and they are expected to be a technology that can improve a patient's quality of life. However, upper limb amputees in Japan are minority. As a result, the development of EMG prosthetic hands has not progressed much because there is little economic demand. Thus, public institutions such as universities and hospitals must respond to the needs of individuals.

The basic actions that humans repeat on a daily basis are called the activities of daily living (ADL). There are seven postures of the fingers that are the minimum needed by humans in their daily lives: power grasps, precision grasps, lateral grasps, hook grasps, tripod grasps, index pointing, and other gestures (e.g., the "V" sign or counting) [2]. To make these postures possible, many degrees of freedom (DOFs) are required. In addition, many DOFs are required for form closure, which is a grasp that fits to an object's shape. It is necessary for grasping objects stably.

However, if the number of DOFs of an EMG prosthetic hand increase, the number of actuators that are required to move the joints also increases. This increases the hand's weight and size. As a result, the hand became difficult to use, and improvements in the quality of life are hindered. Kay mentions that the weight of prosthetic hand should be 370 g or less [3]. Figure 1 shows the relationship between the rate of controllability (ROC) and rate of weight (ROW), which are uniquely defined in this study, for previously proposed multi-DOF hands [2,4–16]. These two metrics can be used to comprehensively evaluate the relationship between the number of actuators and a hand's weight based on DOF: ROC is *M*/*N* and ROW is *W*/*N*, where *N* is the number of DOFs, *M* is the number of actuators, and *W* is the weight of the hand. Figure 1 shows that ROC and ROW are roughly proportional. In conventional research, the weight has been increased by strictly controlling joints. In other words, ROC and ROW are in a trade-off relationship. In this graph, the ideal position of a multi-DOF hand is in the upper left (indicated by the red circle).

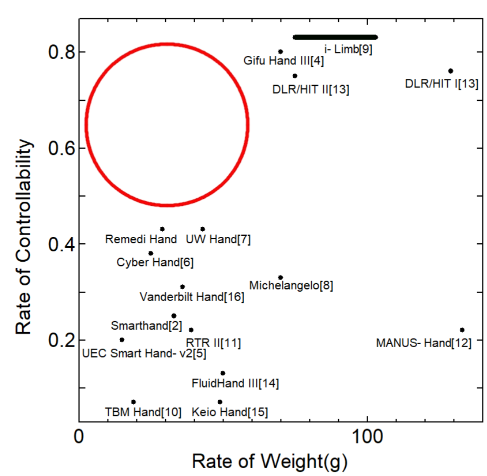

Fig. 1. ROC and ROW values of previously proposed multi-DOF hands.

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The purpose of this study is to develop a multi-DOF hand for EMG prosthetic hands. The hand's weight is less than 370 g, and it can adopt the seven postures listed above. This hand is designed so that its ROC and ROW are within the red circle in Fig. 1.

The next sections present the design and component details of the hand. The Evaluation section shows that our developed hand can achieve the finger postures necessary for ADL.

II. METHOD

A. Conditions of design

Figure 2 presents the model of the hand used in this study. The hand's length was made to match the average length of a Japanese adult's hand.

Of the seven finger postures, power grasps, precision grasps, and lateral grasps can be realized if a hand has two DOFs: the opposition of the thumb carpometacarpal (CM) joint and the flexion/extension of the metacarpophalangeal (MP) joints of the four fingers. A hook grasp needs the flexion/extension of the proximal interphalangeal (PIP) joints of the four fingers to shape the fingers like a hook. Tripod grasps, index pointing, and other gestures require separate control of the flexion/extension of the five fingers. Therefore, a total of 10 DOFs are required to make the seven postures of the fingers. This is the minimum number of DOFs that can enable ADL, so the hand developed in this study has to have them.

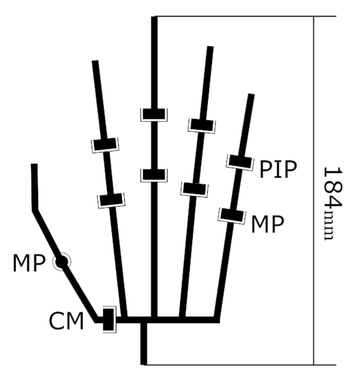

Fig. 2. Model of our developed hand.

Figure 3 shows the state of a human hand grasping an object. When an object is grasped by a human hand, it is mechanically constrained in two directions: the *x*- and *y*-directions. In particular, the *x*-direction is constrained by the arch of the palm. Most robot palms in conventional studies have a flat shape [2,4–6,10–12,14–16]. This study realizes a curve by setting the angles of the carpus in advance. To do this, the carpus needs to move separately from the palm.

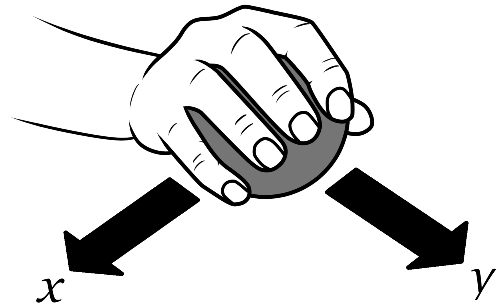

Fig. 3. State of a human hand grasping an object.

B. Wire-Driven Mechanism

In this study, we developed wire-driven mechanism built-in skeleton (WDMBIS). The aim of our approach is to make the hand compact by integrating the wire-driven mechanism and the finger parts of the hand. The WDMBIS has three main components: an actuator, a pulley, and a casing (Fig. 4). The actuator used in the hand is the MG12F1215I298 (Shenzhen Meng Hao Motor, Shenzhen, China). This motor is small in size and lightweight. When winding up the wire, a strong torsional stress is applied to the pulley. The pulley is hence made of aluminum to withstand this force while saving weight. The casing consists of two metallic parts made from stainless steel plates. The casing is necessary to support the wire-driven mechanism and fix the fingers on the carpus of the hand.

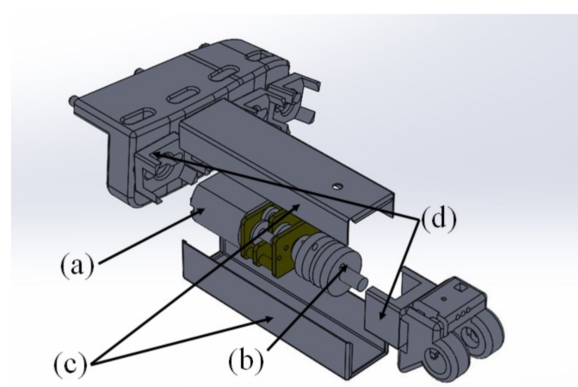

Fig. 4. Configuration of the WDMBIS: (a) actuator, (b) pulley, (c) casing, and (d) end joints of the carpus and finger parts.

Figure 5 presents and overview of the wire-driven system. Two wires for flexion and extension are fixed to the pulley. By winding the wires in alternate directions on the pulley in advance, one wire is released as the other wire is wound up. As long as the wires do not stretch, this system can always maintain a state in which the two wires act in opposition.

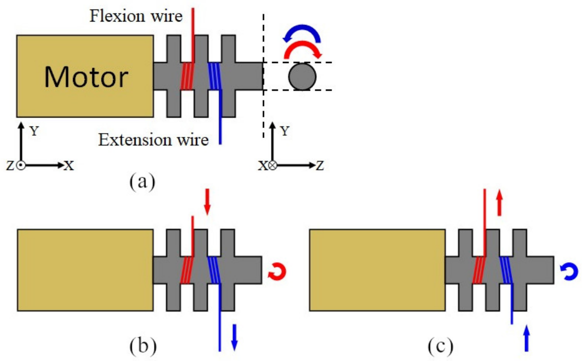

Fig. 5. Overview of the wire-driven system. (a) Configuration of the wire-driven system. (b) The movement of the wires when the finger is flexed. (c) The movement of the wires when the finger is extended.

C. Design of the Fingers

The four fingers—the index finger, middle finger, ring finger, and little finger—have exactly the same design except for the length of the skeleton. Figure 6 shows the design of the index finger. To stabilize the object during precision grasps, the distal interphalangeal (DIP) joint is a passive joint made of an elastic material. The fingertip returns to its original position when the force is removed from it. Moreover, the PIP joints of the four fingers consist of underactuated joints in order to reduce the number of actuators [5]. Each part of the finger is connected by wire.

The black lines in Fig. 7 indicate the wire in each posture of the finger. Because of the WDMBIS structure, the lengths of the wires to be wound up during maximum flexion and extension must be equal. These lengths are calculated as follows:

$$\mathrm{L1} = \mathrm{L2} + \mathrm{L3}, \quad (1)$$
$$\mathrm{L4} = \mathrm{L2} - \mathrm{L5}. \quad (2)$$

It is necessary to determine the wire length from L1 to L5 to satisfy (1) and (2).

The thumb has almost the same design as that of the four fingers except that there is one less joint. Figure 8 indicates the length of the wire during maximum flexion and extension of the thumb. These lengths are calculated as follows:

$$\mathrm{L6} = \mathrm{L7}. \quad (3)$$

Figure 9 shows the moment the switches that detect maximum the flexion and extension of each finger are activated. The switches are installed on both sides of the MP joint. We use the detector switch ESE22MH4XDK (Panasonic, Osaka, Japan). When the switches detect maximum flexion or extension, the motor rotation in that direction is stopped. This prevents destruction caused by excessive flexion and extension.

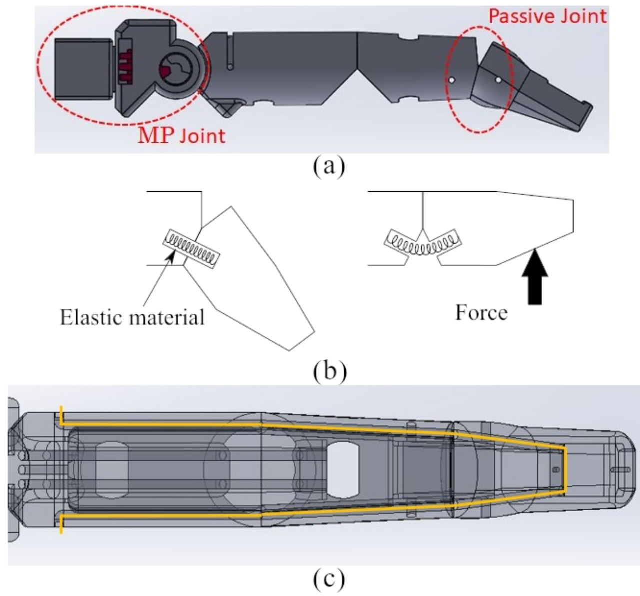

Fig. 6. Design of the index finger. (a) Side view of the index finger. (b) Movement of a passive joint. (c) Wire connecting each part of the finger.

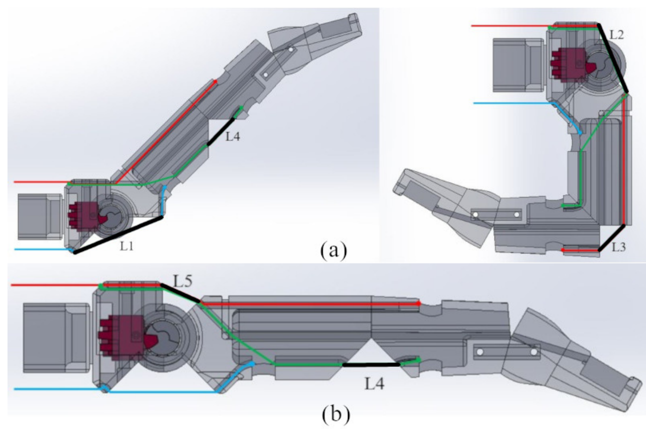

Fig. 7. Length of the wire in each posture of the finger. (a) Maximum flexion and extension and (b) a horizontal pose.

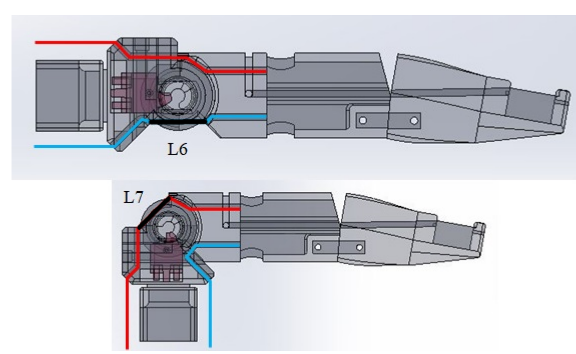

Fig. 8. Length of the wire during maximum flexion and extension.

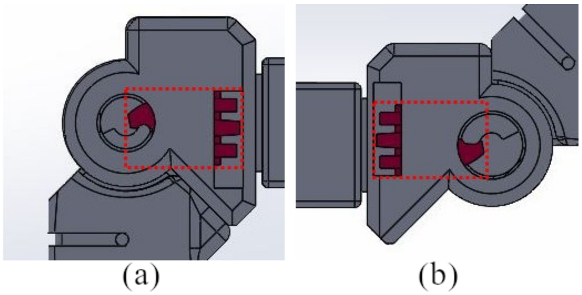

Fig. 9. Moment the switches detect maximum flexion and extension of each finger. (a) Maximum flexion and (b) maximum extension.

D. Carpus and Thumb CM Joints

Each finger is fixed by a WDMBIS to the carpus and the thumb CM (TCM) joint part of the hand. The TCM joint is driven by gears (Fig. 10). To make the posture of the fingers more natural, the end joints of the carpus are rotated, as shown in Fig. 11. Like the MP joints, the TCM joint has switches to prevent damage (Fig. 12).

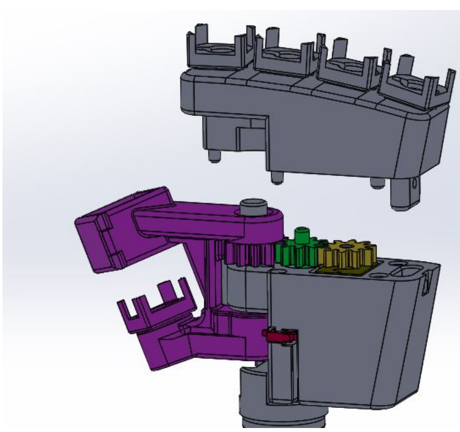

Fig. 10. Internal structure of the carpus.

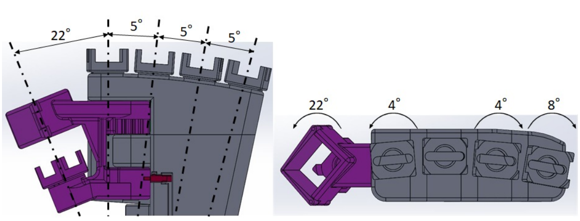

Fig. 11. Rotation of the end joint of the carpus.

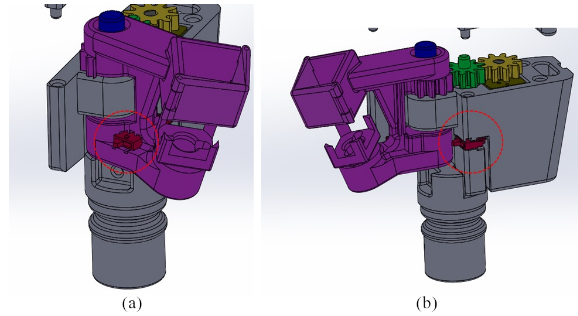

Fig. 12. Position of maximum flexion and extension detection for the TCM joint. (a) Side view of extension and (b) side view of flexion.

E. Prototype of the Hand

Figure 13 shows the hand that we developed in this study. The fingers, carpus, and TCM joint were made with a three-dimensional printer. The material of the fingers is ABS plastic, and the carpus and TCM joint are nylon 66. The weight of the hand was measured to be 188 g. Recalling that the DOF of this hand is 10, ROC and ROW of this hand are calculated to be 0.6 and 18.8, respectively. The position of the prototype hand on the graph in Fig. 1 falls within the red circle, meeting the design requirements.

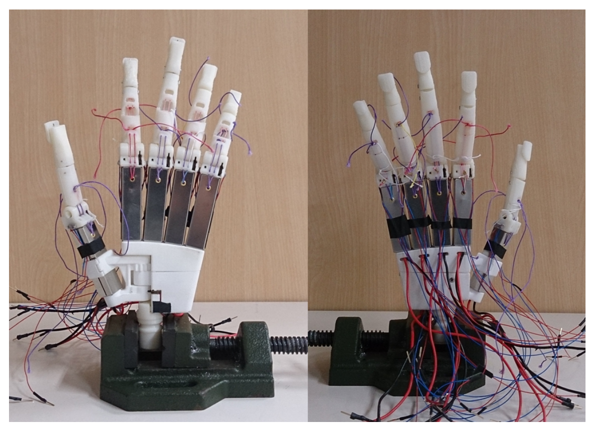

Fig. 13. Hand developed in this study.

III. EVALUATION

To evaluate whether the developed hand can form the required finger postures, we conducted a grasping experiment in which our developed hand grasped objects with various shapes. The hand was driven by a motor (Texas Instruments, DRV8835), and its postures were controlled by a microcomputer (Renesas Electronics, SH7125).

Objects used in ADL were chosen for the experiments. They are listed in Table 1. The hand was fixed to a desk with a vise, as shown in Fig. 13.

Figure 14 shows the results of this experiment. The results reveal that the hand can grasp all the objects and can form all of the required finger postures.

TABLE I
LIST OF OBJECTS USED IN THE EXPERIMENT

Object	Weight (g)	Size (mm)	Grasp type
Empty can	12.8	52.6×133.3	Power
Eraser	17.9	$10.2 \times 23.3 \times 58.8$	Precision
Card	5.1	$54.0 \times 85.6 \times 0.8$	Lateral
Allen wrench	31.2	5.0×167.2	Hook
Marker	13.5	15.6×146.4	Tripod

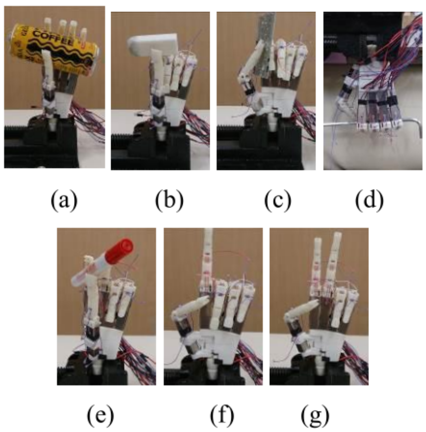

Fig. 14. Results of the grasping experiment. (a) Power grasp, (b) precision grasp, (c) lateral grasp, (d) hook grasp, (e) tripod grasp, (f) index pointing, and (g) other gesture.

IV. DISCUSSION

The results of the grasping experiment demonstrate that our developed hand is able to achieve the seven motions needed in ADL. It can hence be concluded that upper limb amputees can conduct their ADL using our hand. However, because the hand does not have a function that corresponds to thumb MP joint adduction and abduction, it is difficult for the hand to grasp an object with a large diameter. The ROC and ROW of our hand were within the red circle in Fig. 1. This result suggests that the hand satisfies the ideal requirements of a multi-DOF hand.

V. CONCLUSION

In this study, we developed a multi-DOF hand that weighs 188 g and has 10 DOFs. We carried out a grasping experiment to ensure that the hand can form the minimum number of finger postures that are required for humans to perform their ADL. The results show that the hand could perform all required motions. In addition, the developed hand's ROC and ROW are better than those of previously proposed hands, and they satisfy the ideal requirements for a multi-DOF hand. Because the weight of the hand is much lower than required, there is room for improving the hand's performance with a stronger actuator and additional DOFs.

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