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Design of A Prosthetic Hand for Multiple hand Motions *

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***Abstract* - In this paper, a prosthetic hand which has been considered both of multiple hand motions and lightweight was presented. By integrating different digits functions of stable linkage four fingers and adaptive thumb, the proposed hand is capable to realize 10 types of hand motions based on the frequently-used hand motions. Furthermore, the proposed hand is modeled based on an adult hand size, with three motors embedded in the palm. Finally, the experiment had been conducted to verify the motion function and grasp performance.**

Index Terms* –*Multiple hand motions, Prosthetic hand, Lightweight.

I. INTRODUCTION

There are a lot of upper-limb disabled people in the world, who lose hand function due to some congenital or acquired factors like accidents or diseases. With the loss of hand function, their working and daily living has been directly impacted in different extent. As a replacement of the lost hand, the prosthetic hand which can be intuitively controlled by using the amputee's electromyography (EMG) signals, is highly valued [1]. Ideally, the prosthetic hand should be designed with high dexterity as a real human hand, enable to provide various hand motions. However, to completely mimic the human hand seems a big challenge even under the current state of the art, especially as a prosthesis equipped on the residual upper-limb end. The current prosthetic hands can be mainly divided into two types: fully-actuated and under-actuated. The fully-actuated type is often much more dexterous compared to the under-actuated type, owe to multi-actuator configuration corresponded to every degree of freedom (DoF). Whereas, the multi-actuator configuration usually leads to weight increase [2], control complexity, and even package issues. In contrast, many current studies have tended to the latter type, for better satisfaction of lightweight, easy control, and human-size package. Learning from various experimental and commercial under-actuated prosthetic hands [3-8], we realized that through good design, even a configuration of few actuators could meet required hand motions, especially for some frequently used hand motions.

But even so, it's difficult to considerate both lightweight and multiple grasp motions in one prosthetic hand. The fact is, although only take frequently used hand motions into our scope, there are still up to 16 types of frequently-used hand motions [9], as shown in Fig. 1. And as a prosthetic hand, the weight factor should always be carefully considered through the whole design. Kay et al.'s study claimed that the entire weight of a prosthetic hand should be less than 370 g [10].

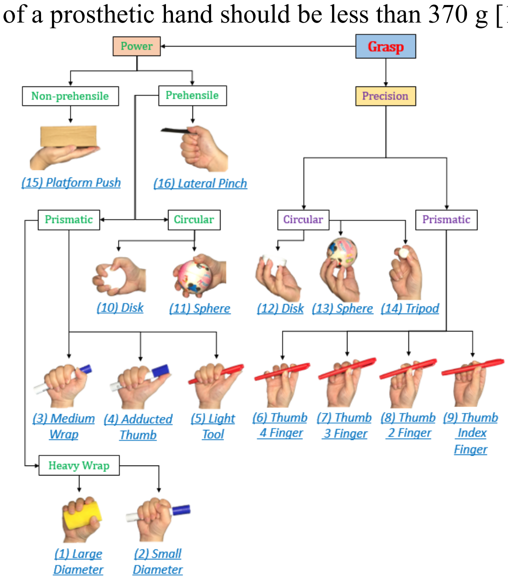

Fig. 1 Frequently-used hand motions (Adapted from [11])

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The purpose of this study is to utilize a few actuators to achieve multiple hand motion as much as possible, to combine both lightweight and hand performance. The proposed prosthetic hand has three servo motors embedded in the palm, which could realize 10 types of hand motions (based on Fig.1), with a weightless than 200 g. Furthermore, considering the aesthetic requirements [12] of the amputees, the hand has been modeled with a human-like appearance, based on an adult's right hand.

In this paper, Section II analyzes the 16 types of frequently-used hand motions to extract the target motions and required number of motors. Section III is about hand design. Section IV describes the control method briefly. Section V shows some evaluations conducted to validate hand performance. Finally, section VI concludes this work.

II. Motion Analysis And Extraction

A. *Motion Analysis*

In Fig.1, two main categories are distinguished for all the hand motions, which are the power grasp and precision grasp. Therefore, the motion analysis will be conducted according to the two kinds of categories respectively. Firstly, there are nine motions in the power grasp category, including non-prehensile and prehensile motions. The prehensile motion is defined that the object is seized and held partly or wholly within the compass of the hand [13]. Hence, "Platform Push" is classified into the former category. Which is a full extension posture, the thumb totally abducted to form a flat plane with other four fingers. Then, we observed the prehensile motions to find the relation of them. "Lateral Pinch": thumb is slightly adducted and contacted the side of index finger, while all the digits are totally flexed; "Disk": using the four fingers' Proximal Interphalangeal (PIP) and Distal Interphalangeal (DIP) joints and adducting the thumb to surround the circular object; "Sphere": all the digits are flexed, and the thumb adducted to oppose position to form an arch [13]; "Medium Wrap": four fingers flexed together, the thumb abducted the side of index finger; "Adducted Thumb": the thumb stays on the abduction position and every joint extends to support the object; "Light Tool" seems similar to "Adducted Thumb", but the IP joint of thumb hyperextended slightly to make the support more stably; "Large Diameter" and "Small Diameter": thumb adducted to opposing position with all digits flexed.

Secondly, for the precision grasp category, all the motions have been classified according to the shape of the object, which is the circular and prismatic grasp. For the former grasp, "Disk" and "Sphere" are very similar: all the digits are flexed, the thumb is adducted, and the hand forms an arch posture. In the "Tripod" grasp, only three fingers (thumb, index, and middle) are flexed to surround a small spherical object. Next, for the later grasp, these grasp motions do not seem to change so much. However, the "Thumb-4 Finger" and "Thumb-3 Finger" are more complex than the other two motions. Because both of them require all the fingertips to arrange on a straight line, which means that digits need to flex with different angles simultaneously.

B. *Motion Extraction*

It is clear that digit joints usually work together during grasping. Such that, using a few motors is enable to involve multiple degrees of freedom (DoFs) for achieving higher dexterity. Based on the motion analysis, the relation of the 16 hand motions can be extracted.

Firstly, the thumb and four fingers should be discussed separately. Because the thumb is a special one among the digits, it can act as a separate unit without involving any other fingers. The thumb has two kinds of independent DoFs, the adduction/abduction of Carpometacarpal (CM) joint and flexion/extension of CM, Metacarpophalangeal (MP) and Interphalangeal (IP) joint. Therefore, at least one actuator is needed for each kind of DoF (degree of freedom), which is counted to two actuators. In addition, notice that the hyperextension of the IP joint is also necessary, especially for "Thumb Index Finger". Thus, in theory, three actuators are required in total for the thumb. Secondly, about the four fingers, although they usually flex synergistically during grasping such as "Medium Warp", "Adducted Thumb" and "Light Tool", they could also act separately to perform some precision grasp, like "Thumb 3 Finger", "Thumb 2 Finger" and "Thumb Index Finger". Thus, in order to enable the MP joint of each finger to act independently, four actuators are needed for one-to-one correspondence form the index to the little finger. Then, because the rest of the PIP and DIP joints usually flex synergistically, one actuator could be enough. Thus, the total required number of actuators for achieving all the 16 hand motions reach up to eight (as shown in Table I).

TABLE I
Correlative DoF of 16 Hand Montions

<table>
<tr><th rowspan="2">Number of Actuators</th><th colspan="3">Correlative DoF of 16 hand motions</th><th rowspan="2">Total Number Of Actuators</th></tr>
<tr><th>Four Fingers</th><th colspan="2">Thumb</th></tr>
<tr><td>1</td><td>PIP & DIP (Flexion)</td><td rowspan="3"></td><td rowspan="4"></td><td rowspan="5">8</td></tr>
<tr><td>1</td><td>Little (MP Flexion)</td></tr>
<tr><td>1</td><td>Ring (MP Flexion)</td></tr>
<tr><td>2</td><td>Middle (MP Flexion)</td><td>IP (Hyperextension)</td></tr>
<tr><td>3</td><td>Index (MP Flexion)</td><td>CM & MP & IP (Flexion)</td><td>CM (Adduction) & Arch</td></tr>
</table>

According to Table I, eight motors are required for realizing all the 16 grasp motions. Although it is not a big number compared to dozens of movable joints in a real human hand, it is still too many for a prosthetic hand. It will inevitably bring some disadvantages like overweight, blocky package, high cost and so on. For this reason, we discard some DoFs to reduce the number of actuators from eight to three. With this change, the proposed hand could not only realize 10 grasp motions but also satisfy the weight and size limitation. In Table II, the Correlative relation between hand motors and DoFs are listed.

TABLE II
CORRELATIVE DOF OF 10 HAND MOTIONS

Number of Actuators	Correlative DoF of 10 hand motions			Total Number Of Actuators
	Four Fingers	Thumb		
3	MP & PIP & DIP (Flexion)	CM & MP (Flexion)	CM (Adduction)	3

III. HAND DESIGN

Based on the motion analysis, three servo motors (Atlas Digital Servo, Hyperion, HK) are adopted due to the benefits of its lightweight, compact shape, and relatively high torque. One is the HP-DS095-FMD type (18.3 g, 4.5 kg/cm), and the other two are the HP-DH13-FMB type (24.5 g, 5.5 kg/cm). As shown in Fig. 2, motor 1 drives the four fingers to flex simultaneously, motor 2 is utilized for the flexion of the thumb, and motor 3 is used for the adduction/abduction of the thumb.

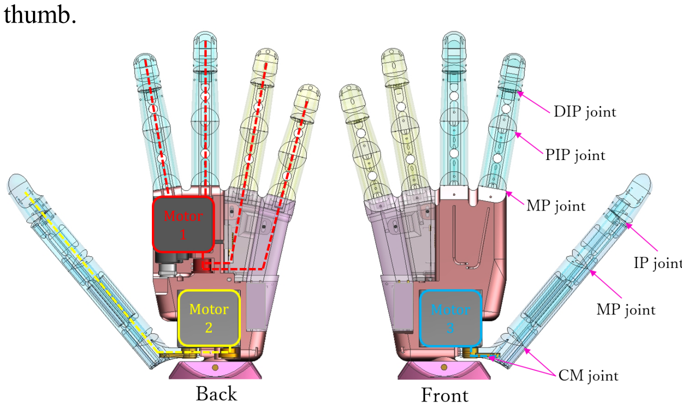

Fig. 2 Configuration of motors

A. Four Fingers

For the four fingers, every finger is composed of three movable joints, which are the MP, PIP, and DIP joints, like the human hand. Motor 1 drives all the three joints simultaneously to provide flexion for grasping. To obtain an exact position during a precision grasp process, three tendons were set up each finger. Because the transmission mechanism from the index to the little finger is exactly the same, only taking one finger as an example here. As shown in Fig. 3, the red tendon connected with a pony roll is fixed on the proximal phalange, the green tendon is fixed on the intermediate phalange through the proximal phalange, and similarly, the blue tendon is fixed on the distal phalange through the intermediate phalange. With the rotation of motor 1, the red tendon rolls up to pull the MP joint to flexion, and the DIP and PIP joint will be pulled to flexion simultaneously. Furthermore, the rotation of each joint always maintains with the same angle because the travel distance of every tendon on both flexion and extension side are the same.

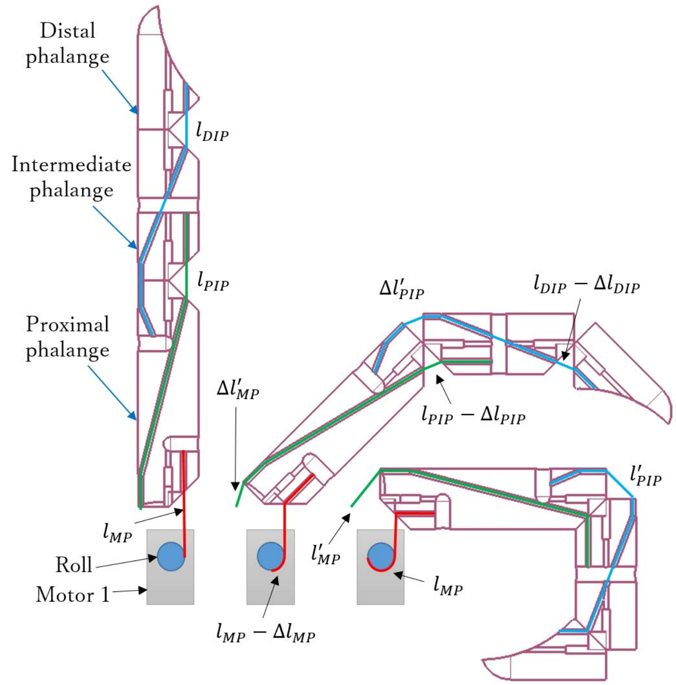

Fig. 3 Constant interlock mechanism

Thus, we can get the following equations:

$$\Delta l_{MP} = \Delta l'_{MP} = \Delta l_{PIP} = \Delta l'_{PIP} = \Delta l_{DIP} \quad (1)$$

The flexion angle of each joint can then be calculated:

$$\theta = \frac{l_{MP}}{r_{MP}} = \frac{l_{PIP}}{r_{PIP}} = \frac{l_{DIP}}{r_{DIP}} \quad (2)$$

To extend digits, one elastic tendon was fixed through the MP, PIP, and DIP joints of each finger. When the three flexion tendons become slack with motor 1 rotates counterclockwise, the elastic tendon will drive digit to extend because of its compliance characteristic. However, this characteristic also leads to an opposite force due to stretching, which means it could obstruct the motion of finger flexion. Therefore, the elastic coefficient should be chosen appropriately. Fig.4 shows the stretching state of the elastic tendon on the complete flexion posture: the yellow line expresses the elastic tendon, and the stretching caused by the flexion is marked with a pink color.

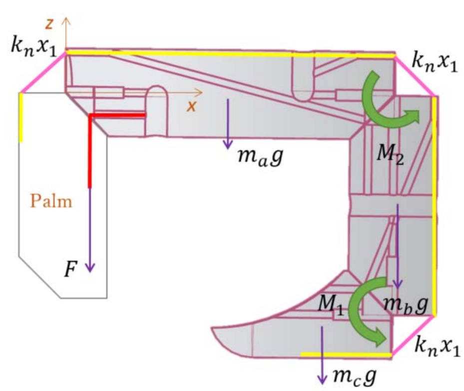

Fig. 4 Totally stretching state in the complete flexion posture

Where x_1 and x_0 are maximum and initial stretching of the elastic tendon; m_a, m_b, and m_c is the gravity of proximal, intermediate and distal phalange, k is the elastic coefficient. Form this state we can find a relationship of the energy changes from the initial state to a totally stretching state, to get a proper elastic coefficient.

B. the Thumb

The thumb also contains three movable joints: the CM, MP, and IP joints, as shown in Fig. 2. There is a drive tendon connected to motor 2 via a roll that passed through every joint of the thumb. In this way, all three joints can be driven as a unit, however, the rotation angle of each joint is indeterminate. This indeterminacy provides an adaptive flexion for the thumb, which relates to better-grasping performance. This means that if one or two joints are blocked due to the contact of an object while grasping, the other joint will keep flexing until they surround the object completely. Fig. 5 shows the adaptive process: if the CM joint is blocked, the drive tendon will keep pulling the MP and IP joint; and if the MP joint is blocked, the tendon force will still transmit to the IP joint.

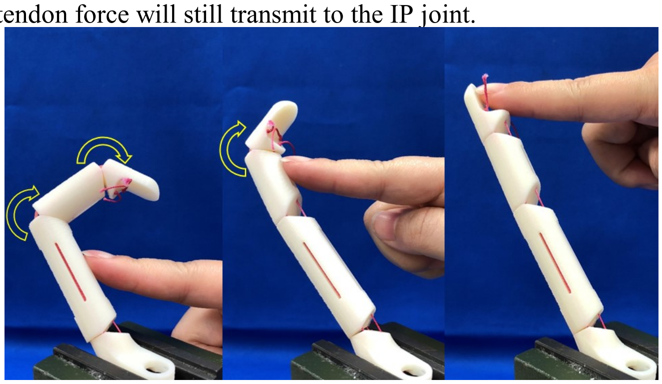

Fig. 5 Adaptive process

C. the Palm

The human palm is formed by the five metacarpal bones, which allows the palm to form an arch, which is very helpful in sphere object grasping. However, adding DoFs to mimic the arch of the palm will increase the motor configurations. In this design, the palm is still considered as a rigid part but modeled with some oblique angles features close to a real human hand. As shown in Fig. 6, the palm has three main body parts, the base holder, ring-finger part and little-finger part. Motor 3 is embedded in the base holder, an axis linker is set on the bottom. Both of the ring-finger and little-finger part are connected to the base holder through a fixed stopper, for assembly and angle adjusting consideration.

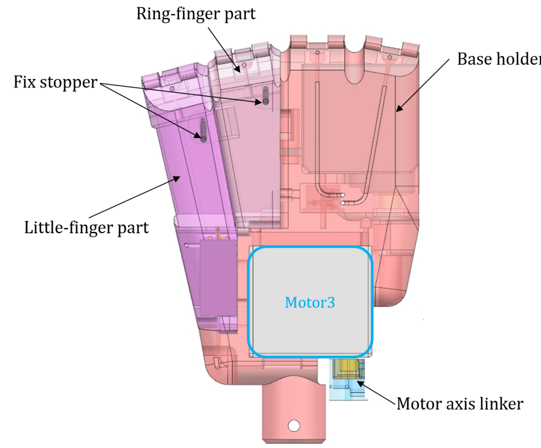

Fig. 6 The palm (front view)

Taken the axis rotation center of motor 3 as the ordinate origin, Fig. 7 shows the sketch when the four fingers assembled onto the palm. Every finger has been set with an oblique angle except the middle finger. Taken the central axis of the middle finger as the reference, the index, and ring finger distributed on both sides of it with an oblique angle of 10 degrees, and the angle little finger is 15 degrees. Therefore, when the four fingers flex, the trajectory is no longer a curve parallel to each other but will form a curve space (shown in Fig. 8). If make every finger stand straightly on the palm, the trajectory will change to Fig. 9. Comparing to the former, it could not provide a curve space wrapping like the human hand did in some sphere grasp. Therefore, this palm design can make the hand grasp sphere object to some extent.

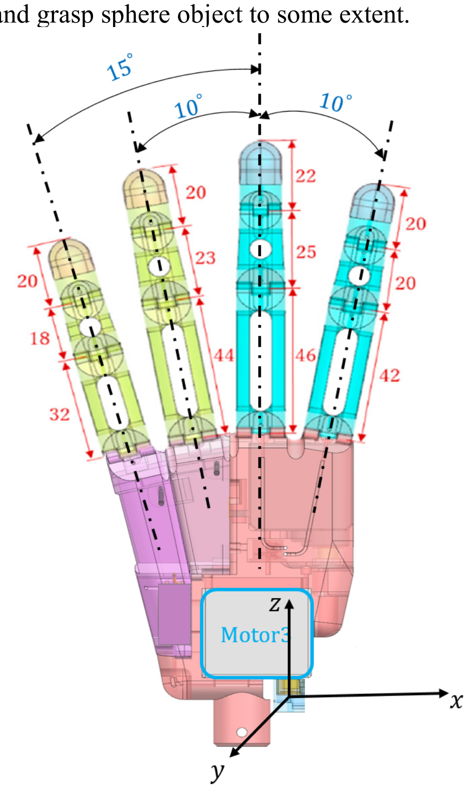

Fig. 7 Sketch of the four fingers and palm

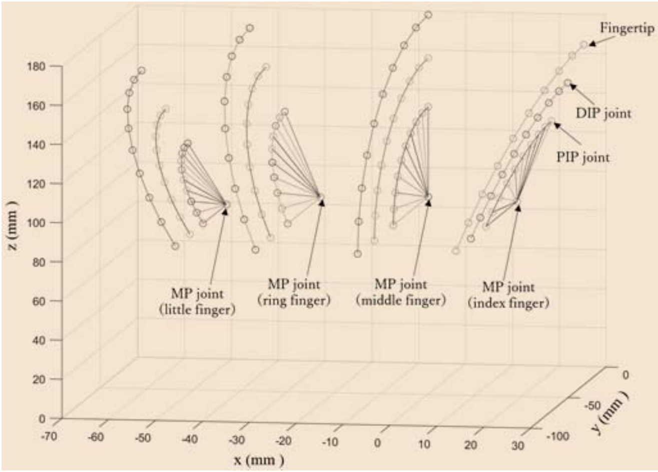

Fig. 8 The trajectory (with oblique angle)

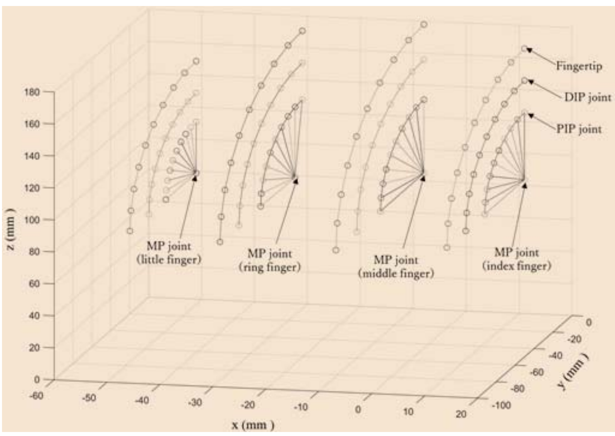

Fig. 9 The trajectory (without oblique angle)

IV. MYOELECTRIC CONTROL

In order to intuitively operate the prosthetic hand, the myoelectric control method was used. Three myoelectric sensors were attached to the skin surface at locations corresponding to the muscles that drive the digits. The EMG signals were taken from these sites with the muscle contractions and then converted to the 2 kHz sampling signal via A/D conversion using a microcomputer (SH72544R, Renesas Electronics Corporation, Japan). With an FFT (Fast Fourier Transform), features of five hand motions, including flexion and extension of the four fingers, adduction, and abduction of the thumb, and relaxing the hand, were extracted. These actions can be combined as hand opening, power grasp, precision grasp, and lateral pinch. These feature quantities are then given as inputs to the three layers of an artificial neural network (ANN), and the most likely motions are determined by identification with the sigmoid function. Finally, based on classification and pattern recognition results, the PWM (Pulse Width Modulation) signal is sent to the motors to control the prosthetic hand.

V. EVALUATION

The purpose of the evaluation is to verify the performance of the proposed prosthetic design. A prototype hand was built, and the total weight is less than 200 g. We firstly conducted the motion test experiment using a motor controller for some grasp tasks, to verify whether the hand could realize 10 hand motions as the design expected. Then, the pick-and-place experiment was carried out, by using intuitive control to grasp some daily used objects.

A. Motion Test Experiment

This part of the experiment focused on whether the proposed hand could realize the 10 expected hand motions. For the experimental setting, the prosthetic hand was fixed on a table, and a motor controller was used to perform the 10 hand motions. The result is shown in Fig. 10, we can see that the hand can perform 10 hand motions.

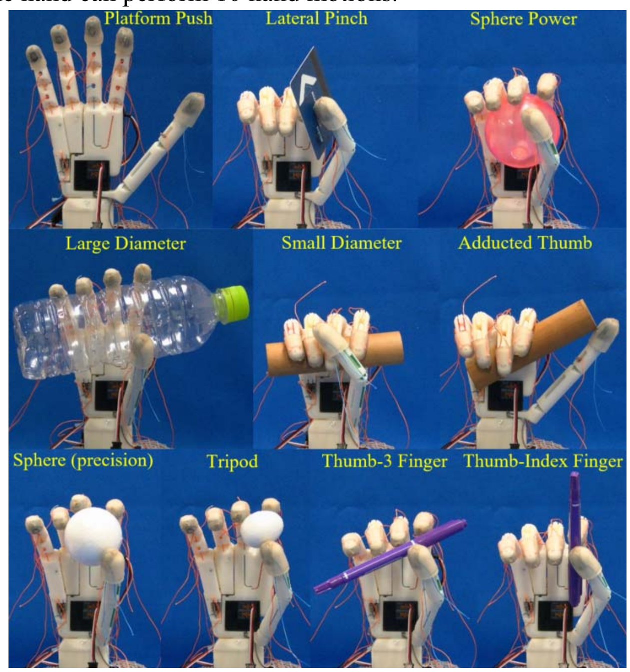

Fig. 10 Realized motions

B. Pick-and-Place Experiment

The pick-and-place experiment was conducted to investigate the stability and operability of grasping with intuitive control through EMG signals. The signals were taken from the right forearm of a healthy male adult. The prosthetic hand was equipped on the forearm via a socket, and the user used the prosthetic hand to grasp and move an object between two specified positions, which were two 15×15 mm square areas marked on a table. The task was to pick up an object in one area and move it to the other area. If the object did not drop during moving, the task would be counted to success. The experiment equipment is shown in Fig. 11, and the objects are shown in Fig. 12. The user was required to move each object as quickly as possible within 30 seconds. However, only successful tasks are counted. The results shown in Fig. 13 indicated that the prosthetic hand is able to grasp some daily used objects. Furthermore, small objects require more subtle posture adjustment, which takes much more time than a power grasp, such that the successful times of bigger objects are more than smaller ones.

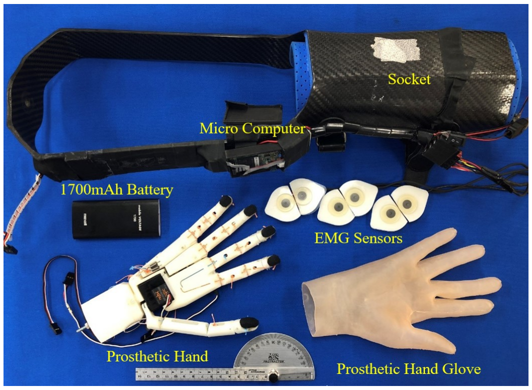

Fig. 11 Equipment for the pick-and-place experiment

Fig. 12 Objects used in the pick-and-place experiment

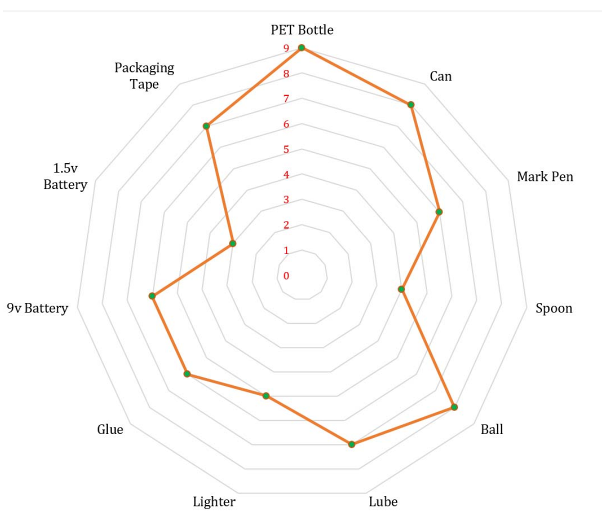

Fig. 13 Results of the pick-and-place experiment

VI. Conclusion

In this study, a prosthetic hand combined the lightweight and multiple hand motions have been proposed. The prosthetic hand can realize 10 of the 16 frequently-used hand motions. Another significant advantage of the proposed design is that it makes the grasp much more natural by adding some human hand feature for the palm. Although the proposed hand is modeled based on adult size, with three embedded motors, the entire weight is less than 200 g. Finally, the performance and practicality of the proposed hand is validated through experiments

Nevertheless, the proposed hand could not provide high grasp power, due to the utilization of small servomotors which is limited by the weight and size limitation. In future work, we will focus on the problem of power optimization and plan to realize much more grasp motions in the next version.

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