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Trans-Radial Prosthesis with Three Opposed Fingers

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***Abstract*— There are body-powered hooks and myoelectric prosthetic hands that trans-radial amputees can use for work. Though the body-powered hooks have good workability for complex operations, the design of the hook is unappealing and the harness is cumbersome. The myoelectric prosthetic hand has a natural appearance similar to the human hand and intuitive operability using a myoelectric control system. However, it is expensive and heavy. Because of these problems associated with prostheses for work, many amputees use cosmetic prostheses. In this paper, we report a lightweight, low-cost electric trans-radial prosthesis with three opposed fingers. A simple mechanism to control the fingers by a linear actuator contributes to its good workability, lightweight, and low-cost. An operation system using an inexpensive distance sensor allows intuitive operability equivalent to the myoelectric control system. A socket makes the prosthesis easily removable. The total weight of the hand and socket is 300 g, and both can be produced with a 3D printer. An evaluation using the Southampton Hand Assessment Procedure (SHAP) demonstrated that an amputee was able to operate abstract objects which require six types of grasps with the developed prosthesis.**

I. INTRODUCTION

There are body-powered hooks and myoelectric prosthetic hands that trans-radial amputees can use for work. The body-powered hook is controlled by a cable control system using motions of the shoulder on the healthy side. It has good workability for complex operations [1]. However, the design of the hook is unappealing and the harness impairs natural movement.

The myoelectric prosthetic hand has a natural appearance similar to the human hand and intuitive operability with a myoelectric control system. In the 1970s, Ottobock produced the Myobock with three fingers. Recently, the Michelangelo hand with five fingers to allow natural hand motions was developed [2]. Similarly, Touch Bionics and RSL Steeper have produced the i-Limb [3] and the bebionic [4], respectively.

Recent research and development are focused on developing myoelectric prosthesis with five fingers [5]–[18]. However, many actuators, complicated mechanisms, and high-performance processors are required in order to achieve an appearance and functionality similar to the human hand. These requirements increase the cost and weight [19]. It is not easy to provide expensive prostheses without public aid. Moreover, amputees tend to discontinue using heavy prostheses [20], [21]. Because of these problems associated with prostheses for work, many amputees use cosmetic prostheses. However, cosmetic prostheses generally have poor functionality and are not convenient. Developing a prosthesis that has the appearance and functionality similar to the human hand is important, but an approach for amputees who need prostheses for work is also important.

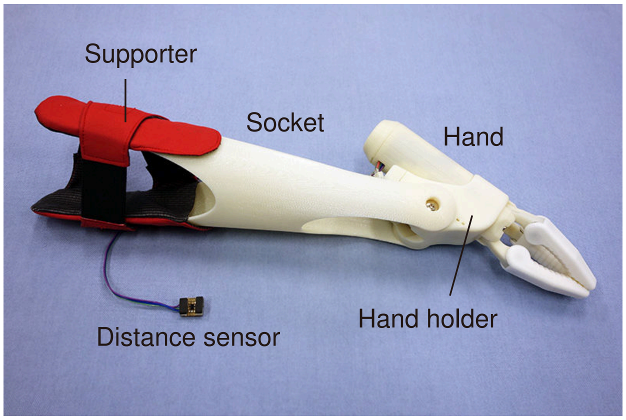

Fig. 1. Appearance of the trans-radial prosthesis (left)

The purpose of our research is to design and develop a lightweight and low-cost trans-radial prosthesis with good workability and operability. In this paper, we report an electric trans-radial prosthesis with three opposed fingers. A simple mechanism to control the three opposed fingers by a linear actuator contributes to its good workability, lightweight, and low-cost. An operation system using an inexpensive distance sensor allows natural operability equivalent to the myoelectric control system. A socket makes the prosthesis easily removable. We also report the results of an evaluation with a trans-radial amputee using this prosthesis.

II. TRANS-RADIAL PROSTHESIS WITH THREE OPPOSED FINGERS

Figure 1 shows the appearance of the electric trans-radial prosthesis with three opposed fingers. It consists of a hand, hand holder, socket, supporter, and distance sensor. The three opposed fingers are driven by a linear actuator. Opening and closing of the fingers are controlled based on distance changes between the distance sensor and the skin surface during muscle contraction. The socket can be worn easily by tightening the supporter. Figure 2 shows the sectional view of the hand and the hand holder that contains a battery and

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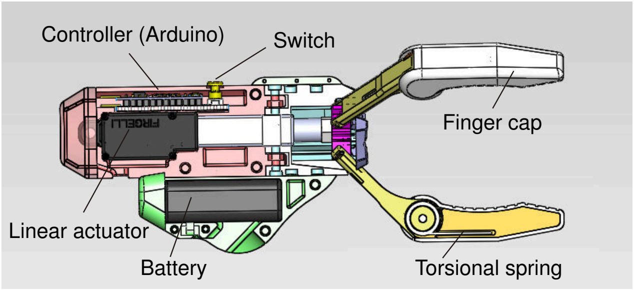


Fig. 2. Sectional view of the hand

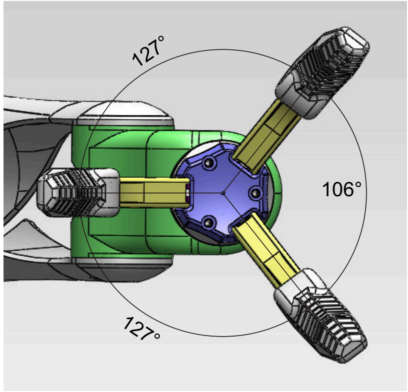


Fig. 3. Front view of the hand (left)

controller. We describe the details of each component in the following subsections.

A. *Hand with Three Opposed Fingers*

The hand grasps objects by opening and closing the three opposed fingers simultaneously. Figure 3 shows the front view of the hand when the fingers are opened maximally. The Y-shaped arrangement of the three fingers makes it easy to grasp cylindrical objects, such as plastic bottles. As shown in Figure 4, the popular prosthesis with three fingers (e.g., Ottobock's System Electric Hand [22]) can only grasp an object in one direction without rotation. In contrast, the developed hand can grasp objects in three directions. Because amputees are not generally good at pronation/supination of the forehand, this arrangement contributes to the workability.

Figure 5 shows the mechanism for opening and closing the fingers. The rod of the linear actuator (L12-R, Firgelli Technologies Inc [23]) is connected to link 2 of the three opposed fingers through link 1. The three opposed fingers are opened depending on the rod extension of the linear actuator. This simple mechanism reduces the weight and cost of the hand. Table I lists the specifications of the linear actuator.

Silicon fingertip caps and torsional springs in the finger joint permit flexible grasping, as shown in Figure 6. As shown in this figure, various objects can be grasped by the hand.

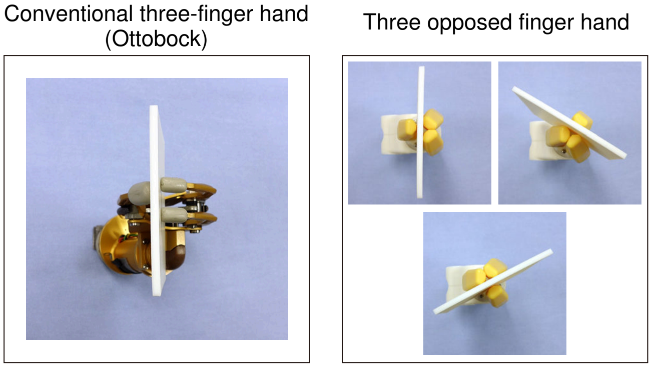


Fig. 4. Comparison of possible grasp patterns between a conventional three-finger hand and developed hand

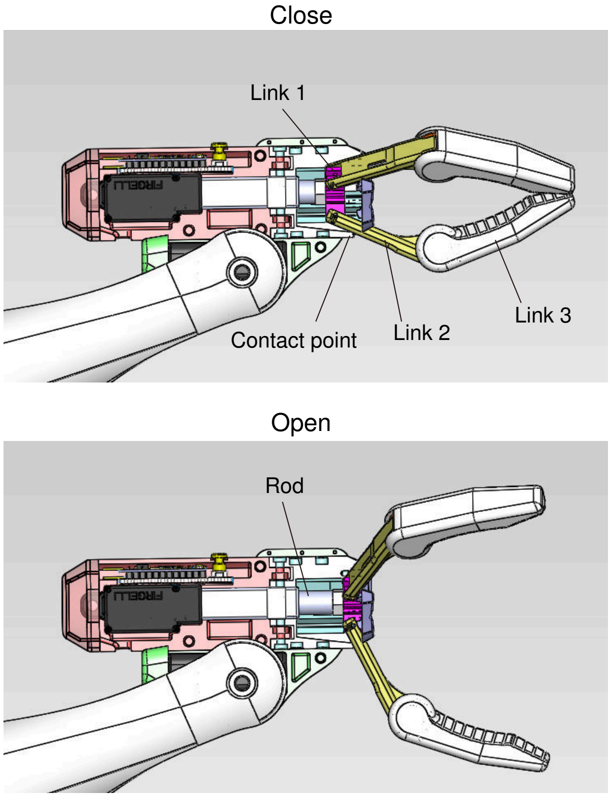


Fig. 5. Mechanism for opening and closing of fingers

B. *Operation System Using Distance Sensor*

Opening and closing of the fingers are controlled based on distance changes between the distance sensor and the skin surface through muscle contraction. Figure 7 shows the structure of the distance sensor. To maintain constant distance between the distance sensor and the skin at rest, sponge material spacers are placed above and below the photo reflector (SG-105, KODENSHI) that measure distance. This distance sensor is placed over the skin where the muscle bulge is observed during contraction of a muscle, such as the flexor carpi ulnaris. When using the non-contact distance sensor, sweat does not affect the signal processing and metal

TABLE I

SPECIFICATIONS OF LINEAR ACTUATOR

Stroke	30 mm
Gear ratio	100:1
Maximum force	23 N
No-load speed	12 mm/s

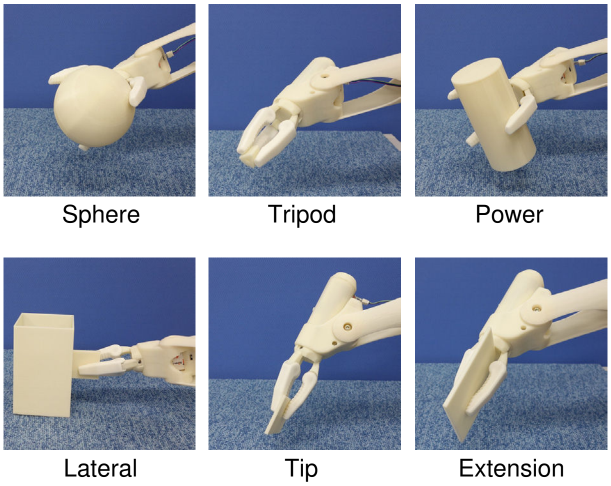


Fig. 6. Six types of grasps using the developed hand

electrodes are not directly touching the skin unlike conventional myoelectric sensor. Moreover, the photo reflector is inexpensive compared to conventional myoelectric sensors.

The operation system to control the fingers is implemented on the processor (Arduino Pro Mini) in the hand. Figure 8 shows the flow chart of the operation system. Pushing the button of the hand for 1 s starts the calibration. First, the distance sensor values at rest are acquired for 1 s while pushing the button briefly, and these are averaged. Next, the distance sensor values during muscle contraction are acquired for 1 s while pushing the button again, and these are also averaged. Finally, using both parameters, a drive parameter is calculated. Because this calibration process is completed with three button operations, users can do this on their own in 5 s. The fingers are opened in proportion to the level of muscle contraction as the voluntary-open system in the body-powered hook. The amount of rod extension is calculated using the drive parameter and the value of the distance sensor, which are sent to the servo linear actuator.

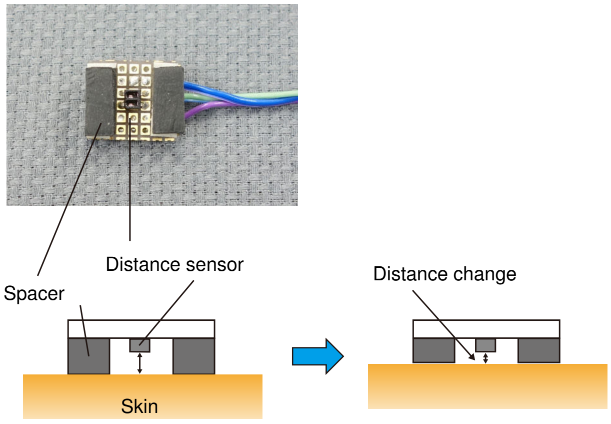


Fig. 7. Photograph and structure of the distance sensor

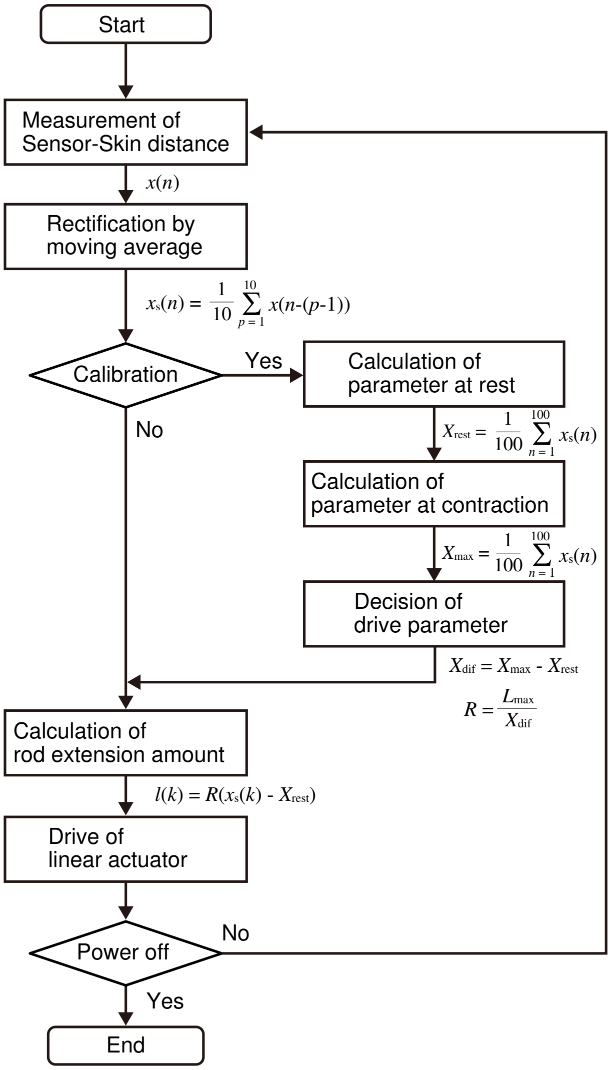


Fig. 8. Flow chart of the operation system

C. Socket and Hand Holder

Figure 9 shows the socket and the hand holder. The socket has a structure sandwiching the radius and ulnar with the socket frame. The slit makes the size adjustable. The socket can be worn easily by tightening the supporter. The inner side of the supporter is lined with high frictional fabric (Daiya Industry) to prevent the socket from falling out of user's stump. The hand holder has wrist flexion/extension mechanism.

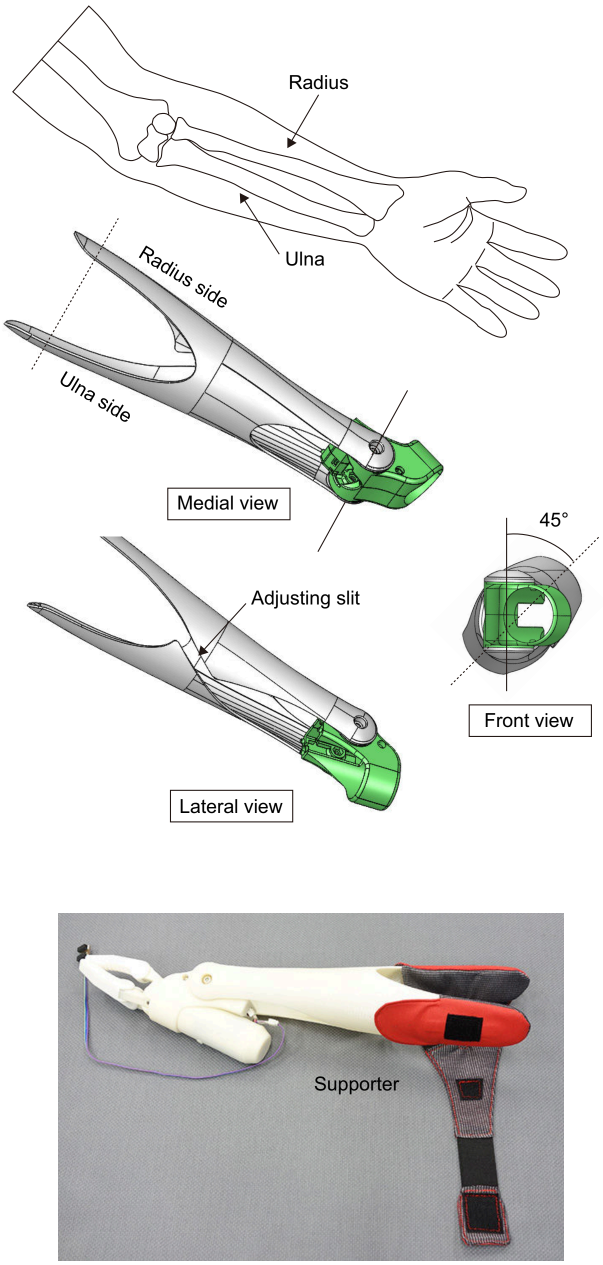


Fig. 9. Socket and supporter

D. Specifications

Most parts of the prototype are made of ABS resin using a 3D printer (uPrint plus, Stratasys Ltd.). The layer thickness of the 3D printer is 0.254 mm. The body of the linear actuator, shafts connecting link 1 and link 2, torsion springs, and screws are the only metal objects in the prosthesis. Table II presents the specifications of the prototype. The total weight of the hand and socket is about 300 g. The life of the lithium-ion battery (500 mAh) powering the prototype is about 6 h. The maximum pinch force is 5-7 N, as shown in Figure 10. The total cost of the material and parts is less than 40,000 yen (400 USD).

TABLE II

SPECIFICATIONS OF THE DEVELOPED PROSTHESIS

Weight (hand and socket)	300 g
Time from closing to opening	1 s
Battery life (500 mAh)	6 h
Max pintch force	5-7 N

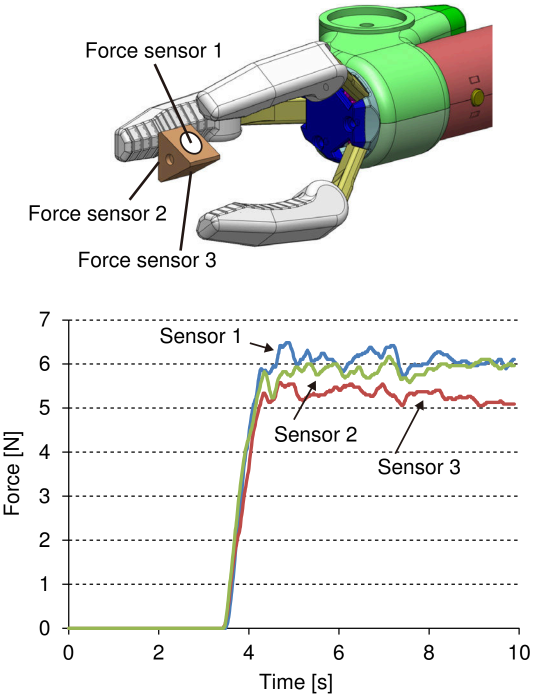


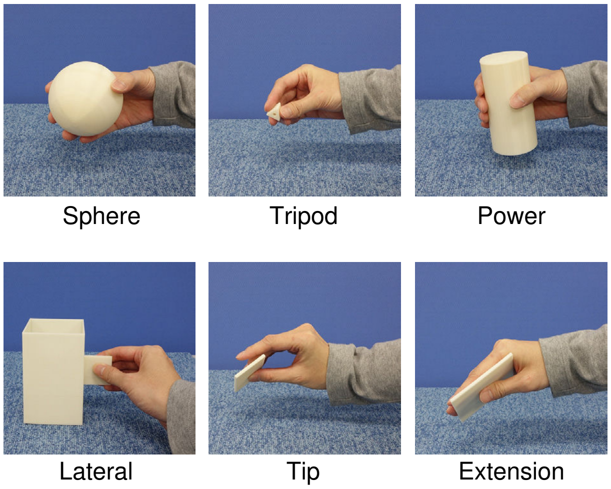
Fig. 10. Pinch force measured using force sensors

III. EVALUATION

To verify the effectiveness of the developed prosthesis, we conducted a Southampton Hand Assessment Procedure (SHAP) [24], [25] test with a trans-radial amputee. The SHAP has been designed based on the analysis of grasp patterns, and their frequency of use in activities of daily living (ADL) tasks. Therefore the SHAP is considered to cover the wide range of tasks that the hand usually undertakes. The test is divided into two sections: abstract object tasks and simulated ADL tasks. The abstract object tasks consist of the manipulation of six types of objects, as shown in Figure 11. These objects reflect specific grasp patterns. In this paper, we report the results of the abstract tasks.

A. Participant

A left trans-radial amputee (male, in his 60s, right-handed) participated in the experiment. His stump length is 12 cm. He usually uses a cosmetic prosthesis and has no experience using prostheses for work. The distance sensor was fixed over his flexor carpi ulnaris with an under lap. He then wore the socket and calibrated the operation system. Figure 12 shows a photograph of the participant wearing the developed


Sphere Tripod Power

Lateral Tip Extension

Fig. 11. Six types of grasps used in SHAP test

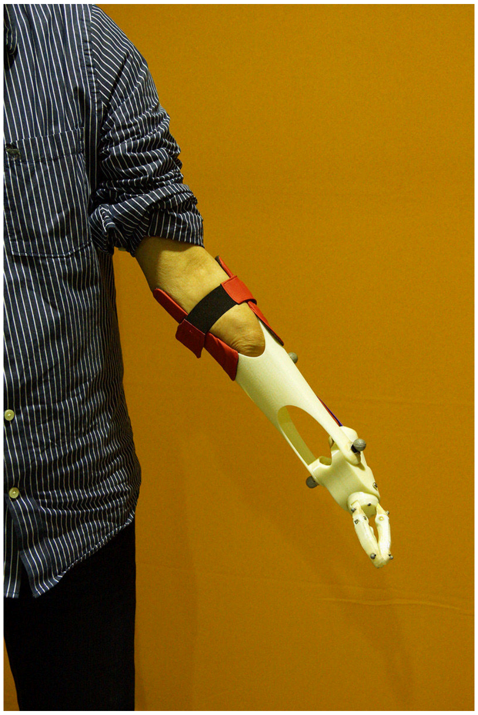


Fig. 12. Photograph of participant wearing the developed prothesis (Markers are mounted for motion capture)

prosthesis. He could wear the prosthesis by himself. The angle of wrist flexion/extension was fixed at 45°. Figure 13 shows the sensor-skin distance value of the participant during muscle contraction. The sensor-skin distance values are increased by muscle contraction.

The experimental protocol of this study was approved by the research ethics boards of the National Rehabilitation Center for Persons with Disability and National Institute of Advanced Industrial Science and Technology. Informed consent was obtained from the participant before participation in the study.

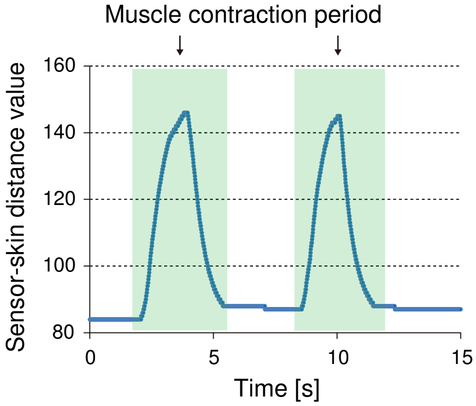


Fig. 13. Sensor-skin distance value of the participant

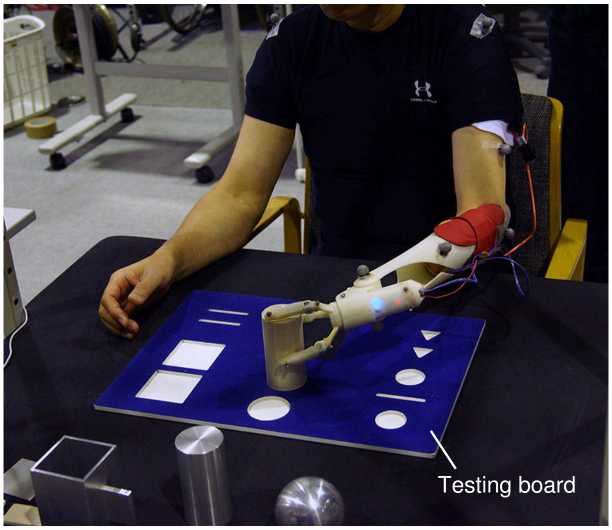


Fig. 14. Photograph of SHAP test

B. Results

In the abstract object tasks, the time to move six objects made of wood (light) or metal (heavy) from the rear slot on the board to the front slot was recorded. The participant practiced for about 10 min before the test. Figure 14 shows the environment of the SHAP test. Table III presents the results of the tasks. All light-object tasks were completed in 7 s. All heavy-object tasks except for the lateral pinch task were completed in 10 s. The lateral pinch task seemed to be difficult for the participant because he had to grasp the slippery handle of the object away from the center of gravity. To complete the lateral pinch task, it is necessary to change rigid material and use a high-torque actuator.

Experimental results showed the trans-radial amputee was able to operate abstract objects which require six types of grasps with the developed prosthesis. The operation system using the distance sensor allowed the participant to operate the prosthesis intuitively after about 10 min of practice. In addition, the socket was able to support the short stump of the participant during object-grasping tasks.

TABLE III

RESULTS OF ABSTRACT OBJECT TASKS

Grip type	Time [s] (Weight [g])			
	Light		Heavy	
Sphere	5.1	(18)	9.8	(530)
Tripod	5.1	(1)	6.5	(21)
Power	4.8	(12)	8.1	(530)
Lateral	6.0	(2)	Failure	(143)
Tip	6.2	(1)	5.0	(71)
Extension	6.5	(21)	6.1	(236)

IV. CONCLUSIONS

In this paper, we reported a lightweight and low-cost electric trans-radial prosthesis with three opposed fingers. A simple mechanism to control the three opposed fingers by a linear actuator contributes to its good workability, lightweight, and low cost. An operation system using an inexpensive distance sensor allows operability equivalent to the myoelectric sensor. A socket makes the prosthesis easily removable. The total weight of the hand and socket is 300 g, and both can be produced with a 3D printer. An evaluation using the SHAP test demonstrated that an amputee was able to operate abstract objects which require six types of grasps with the developed prosthesis.

In future studies, we will improve stiffness of the hand, and evaluate the prosthesis with more amputees in their daily life in terms of usability, durability, and versatility. We also plan to make total design more sophisticated considering adaptability to the human body.

ACKNOWLEDGMENT

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