Finch: Prosthetic Arm With Three Opposing Fingers Controlled by a Muscle Bulge

Masahiro Yoshikawa, *Member, IEEE*, Kazunori Ogawa, Shunji Yamanaka, and Noritaka Kawashima

***Abstract*— Forearm amputees can use body-powered hooks and myoelectric hands for their daily activities. The body-powered hooks are suitable for delicate manipulation. However, their appearance is not always preferred by amputees, and a harness to pull a control cable is not easy to wear. Although the myoelectric hands have a natural appearance similar to the human hand and can be intuitively controlled by a myoelectric control system, they are not easy to try out and are heavy. This paper reports on the Finch, a prosthetic arm with three opposing fingers controlled by a muscle bulge. The aim of developing the Finch is to realize a lightweight prosthetic arm that is easy to wear and use. Three opposing fingers are controlled according to the degree of muscle bulge measured with a muscle bulge sensor on the user's forearm caused by muscle contraction. A supporter socket, consisting of a resin socket frame and a fabric supporter, allows easy fitting. A simple design using a linear actuator and 3D-printed parts achieved light weight (330 g) and low cost. Six functional tests and user tests using Southampton Hand Assessment Procedure showed that the Finch had a practical function that could be used in daily activities.**

***Index Terms*— Prosthetic hand, upper limb prosthesis, socket, single actuator, terminal device.**

I. Introduction

FOREARM amputees can use body-powered hooks and myoelectric hands for their daily activities. The body-powered hooks are controlled by a cable control system using the movement of healthy body parts and are suitable for delicate manipulation. However, the appearance of the hook is not always preferred by amputees, and a harness to pull a control cable is not easy to wear and is uncomfortable.

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethical Review Board of the Osaka Institute of Technology under Approval No. 2018-80.

Masahiro Yoshikawa is with the Graduate School of Robotics and Design, Osaka Institute of Technology, Osaka 5308568, Japan (e-mail: masahiro.yoshikawa@oit.ac.jp).

Kazunori Ogawa is with Daiya Industry Company Ltd., Okayama 7010203, Japan.

Shunji Yamanaka is with the Institute of Industrial Science, The University of Tokyo, Tokyo 1538505, Japan.

Noritaka Kawashima is with the Research Institute, National Rehabilitation Center for Persons with Disabilities, Saitama 3598555, Japan.

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The myoelectric hands are intuitively controlled by a myoelectric control system and have a natural appearance similar to the human hand. In the 1960s, Ottobock introduced a myoelectric hand with a basic grasping function. Then it released Michelangelo [1] that allowed seven different grasps with an electronically positionable thumb. Similarly, the commercially available i-limb [2], bebionic [3], and TASKA [4] have five independently articulating fingers to allow natural hand motions. Many studies in research institutions also focus on developing five-fingered hands [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]. For example, the SmarHand [13] allowed thumb flexion/extension, thumb abduction/adduction, index finger flexion/extension, middle, ring, and little finger flexion/extension with four actuators. Most of the studies have aimed to increase the degrees of freedom (DOFs) to improve the dexterity of prosthetic hands.

Although the myoelectric hands solve some problems with the body-powered hooks, they require multiple actuators, complicated mechanisms, and powerful processors to achieve appearance and functionality similar to those of the human hand. They cause heavyweight and expensive price. The total weight of a commercial myoelectric hand with a socket and battery is generally more than 800 g, which is a reason why users give up using prosthetic hands [18]. Even the lightest myoelectric hand prototype [7], which weighs 312 g, would be over 700 g with a socket and battery. Without public subsidies or insurance, it is difficult for amputees to obtain expensive prosthetic hands.

In addition, it is not easy for amputees to try a myoelectric hand. A socket, which is the interface between a user and a prosthetic hand, is made by casting and is typically adjusted several times for each user. In order to detect the myoelectric signals, electrodes must also be fixed to the proper position in a socket.

Due to the abovementioned problems with conventional prosthetic hands, several amputees use a cosmetic prosthetic hand that lacks a grasping function. While it is essential to develop anthropomorphic electric prosthetic hands that have the appearance and functionality of a human hand, it is also essential to develop an electric prosthetic hand that is lightweight, easy to obtain, wear, and use with a non-anthropomorphic approach. Such a hand would provide a new alternative for amputees.

This paper reports on the Finch, a prosthetic arm with three opposing fingers controlled by a muscle bulge. The aim of developing the Finch is to realize a prosthetic arm that is lightweight, easy to obtain, wear and use with

Fig. 1. Finch consists of a hand, supporter socket, and muscle bulge sensor.

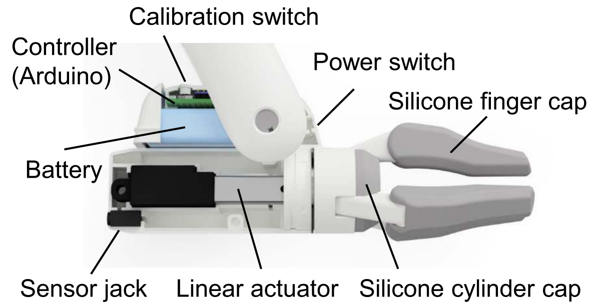

Fig. 2. Sectional view of the hand of the Finch.

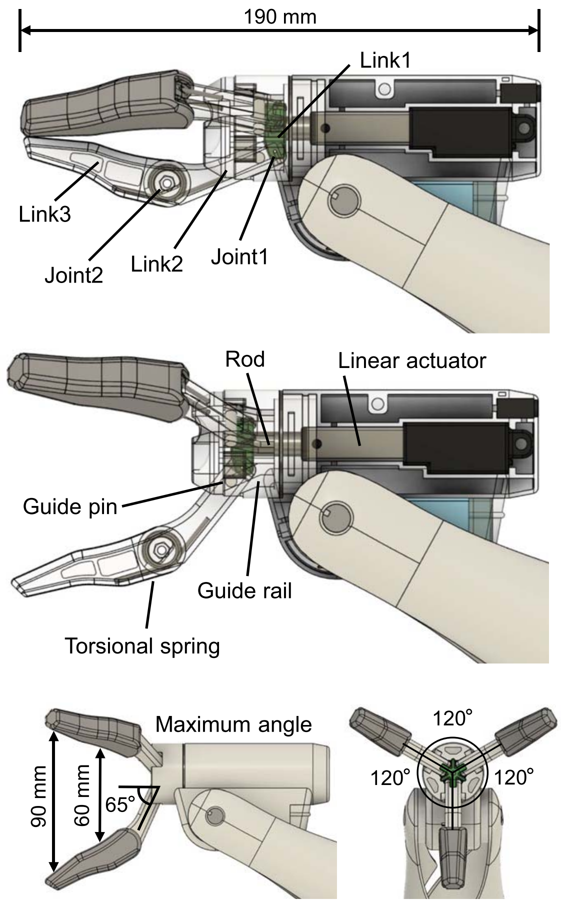

Fig. 3. Mechanism for opening and closing the fingers. The three opposing fingers are simultaneously opened according to the rod extension of the linear actuator.

a non-anthropomorphic approach. The Finch achieves this with a hand with three opposing fingers, a muscle bulge control system, and a supporter socket.

A simple mechanism underactuating three opposing fingers with a linear actuator allows grasping various objects while ensuring lightweight. Hands with three opposing fingers have been developed for industrial robots [19], [20], [21], and their effectiveness in prosthetic hands has not been shown. To be used as a prosthetic hand, an actuator, battery, and controller should be integrated into the hand, and the fingers should be easily replaceable for repair. Although our research group reported a three-fingered prosthetic hand in 2013 [22], its effectiveness as a prosthetic hand was not sufficiently demonstrated.

The three fingers are controlled according to the degree of the muscle bulge measured with a muscle bulge sensor on the user's forearm. Previous studies have used force myography (FMG) with multiple force sensors to control a prosthetic hand [23], [24], [25]. This study shows how to control the Finch with a muscle bulge sensor based on a single photoelectric sensor.

The supporter socket into which users insert their stump (residual limb) provides easy fitting. It consists of a resin socket frame and a fabric supporter covering the socket frame, and it is worn by tightening the supporter straps.

This paper reports that six functional tests and user tests using the Southampton Hand Assessment Procedure (SHAP) by five forearm amputees demonstrate that the Finch has a practical function that can be used in daily activities.

II. Design

The Finch consists of a hand, muscle bulge sensor, and supporter socket, as shown in Fig. 1. The hand has three opposing fingers driven by a linear actuator. The opening and closing of the fingers are controlled based on the degree of the user's muscle bulge measured with the muscle bulge sensor. The supporter socket can be worn by tightening the supporter straps. Fig. 2 shows the sectional view of the hand. It contains a linear actuator, battery, and controller. The hand was designed to grasp a load of 500 g, which can cover many daily objects. In the following subsection, we describe the details of each component.

A. Hand With Three Opposing Fingers

The mechanism for opening and closing the fingers is shown in Fig. 3. A rod of the linear servo actuator (L12-R, Actuonix Inc.) is connected to a link1. The link1 is connected to a link2 at a joint1 of each finger. The link2 is connected to a link3 that extends from 30° (default) to 0° at a joint2. The link1, link2,

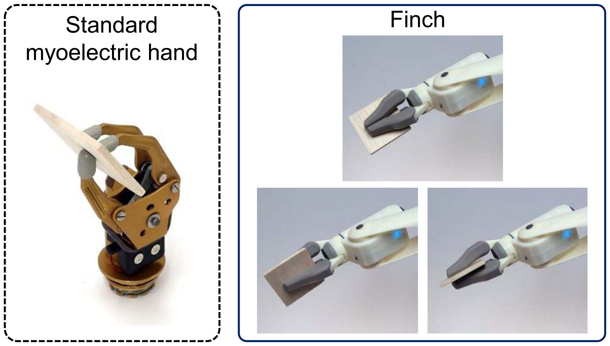

Fig. 4. Comparison of possible grasping patterns between a standard myoelectric hand and the Finch. The standard hand grasps the object in only one direction without rotating the wrist. The Finch can grasp the object in three directions.

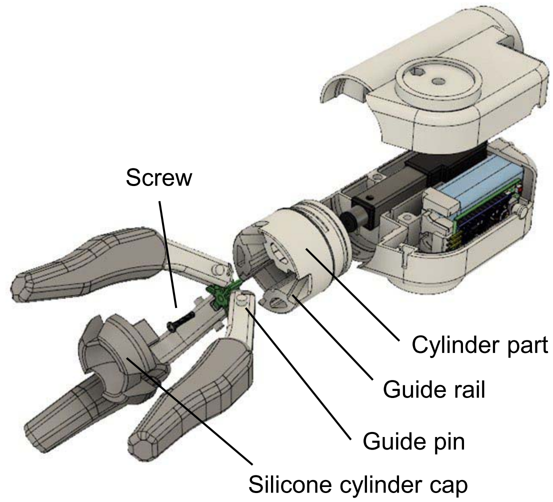

Fig. 5. Exploded view of the Finch.

and link3 are made of acrylonitrile butadiene styrene (ABS) resin. A stainless steel torsional spring (11.5 N · mm/deg) is inserted into the joint2 to increase elasticity. The fingers are covered with silicone caps (thickness of 0.9 mm). The axis of the joint1 is a stainless steel pin (diameter of 1.6 mm), and its ends are bent for retention. The axis of the joint2 is a stainless steel screw (M2.6).

The three opposing fingers open and close simultaneously, according to the rod extension of the linear servo actuator. The actuator holds its position when an overcurrent (460 mA) is detected, or power is removed. The polyacetal guide pin of the link2 slides on the guide rail to control the trajectory of the fingers. The maximum opening width of the fingers is 90 mm to grasp a standard plastic bottle. The passive maximum opening width of the fingers is 100 mm because the link3 passively extends from 30° to 0°.

The three fingers are arranged in an equilateral triangle. As shown in Fig. 4, standard myoelectric hands (e.g., Ottobock's System Electric Hand) grasp the object in only one direction without wrist rotation. Conversely, the Finch can grasp the object in three directions without wrist rotation. Since amputees are generally not good at pronating and supinating the forearm, this arrangement contributes to workability.

The cylinder part is sandwiched between the two body parts (Fig. 5), and the fingers can be manually rotated up to ± 100° according to the user's preference. It was covered with a tapered and pitted silicone cylinder cap to support grasping. Three fingers can be replaced by removing the screw.

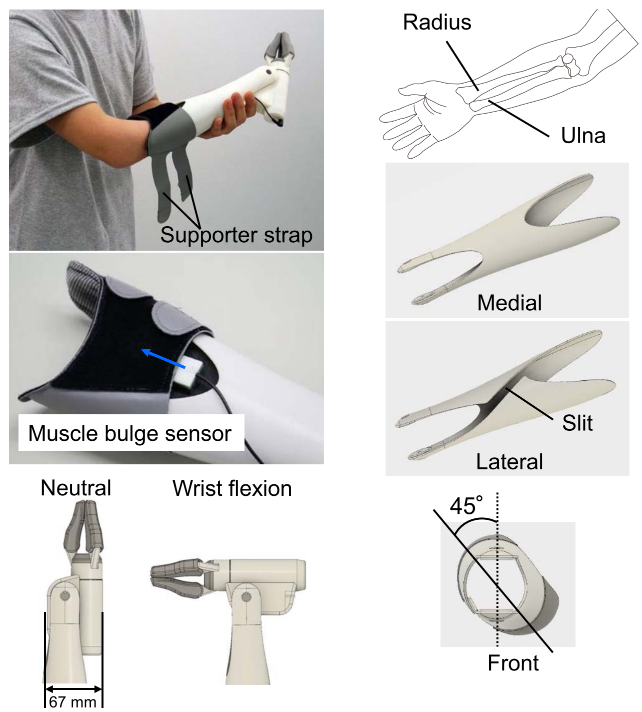

Fig. 6. Supporter socket consists of the resin socket frame and the fabric supporter. A user can wear the Finch by tightening the supporter straps.

B. Supporter Socket

The supporter socket, into which the user inserts a stump, consists of an ABS resin socket frame and a fabric supporter covering the socket frame, as shown in Fig. 6. It is worn by tightening the supporter straps and provides an easy fit. There are five sizes (XS, S, M, L, and XL), and the slit in the socket frame and the thickness of the supporter allow fine adjustment.

The socket frame has a structure sandwiching the radius and ulnar and is twisted by 45° based on the anatomical structure of the forearm. It has a wrist joint that allows passive wrist flexion and extension. When the wrist angle is 0°, the width is 67 mm, and it is possible to wear long sleeves when wearing the Finch.

The supporter has a pocket into which the muscle bulge sensor is inserted. The inside is lined with frictional fabric (Daiya Industry Co. Ltd.) to prevent the supporter socket from slipping off the user's stump. It can be washed and is therefore clean compared to the regular socket of a myoelectric prosthetic arm.

C. Muscle Bulge Control System

The opening and closing of the fingers are controlled based on the muscle bulge caused by muscle contraction. Fig. 7 shows the structure of the muscle bulge sensor. It measures

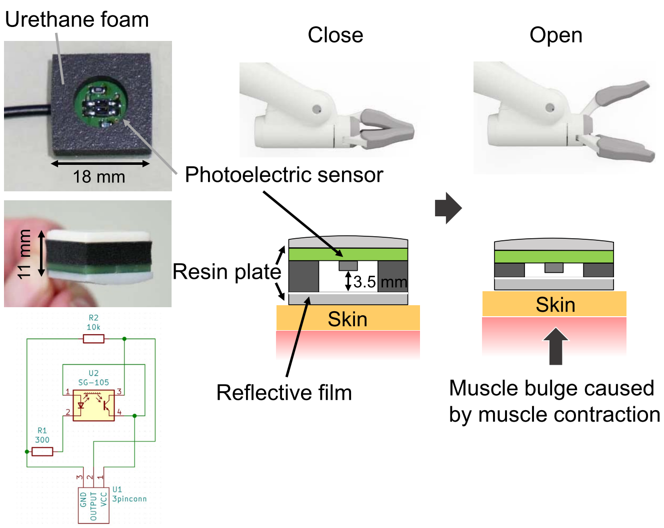

Fig. 7. Muscle bulge sensor measures the distance from the photoelectric sensor to the ABS resin plate. The elastically deformable urethane foam is placed around the photoelectric sensor and expands and contracts in response to the muscle bulge.

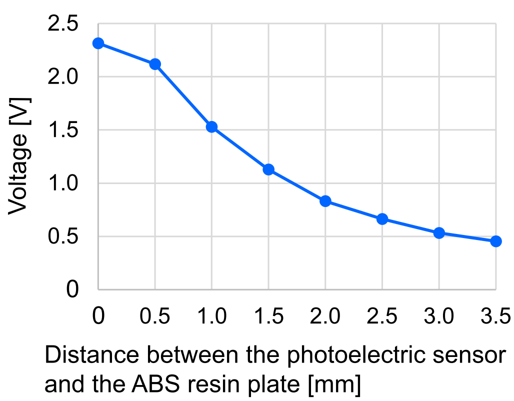

Fig. 8. Relationship between the voltage and the distance from the photoelectric sensor to the ABS resin plate.

the distance from a photoelectric sensor (SG-105, Kodenshi Corp.) on the board to an ABS resin plate. A reflective film (AHW001, Waki Sangyo Co. Ltd.) is attached to the plate to suppress the effect of light from outside. An elastically deformable urethane foam (PORON LE-20, Rogers Inoac Corp.) is placed around the photoelectric sensor, and it expands and contracts in response to the muscle bulge. A 300 Ω resistor is placed on the LED side, and a 10 kΩ resistor is placed on the phototransistor side of the board. Fig. 8 shows the relationship between the voltage and the distance from the photoelectric sensor to the ABS resin plate. The sensor is generally used in the range of 0.5 mm to 3.0 mm. The muscle bulge sensor is placed over a muscle, such as the flexor carpi ulnaris muscle, where a muscle bulge is observed during muscle contraction. The sensor is typically inserted into the pocket of the abovementioned supporter.

With conventional myoelectric sensors, sweat causes discomfort and skin irritation because metal electrodes directly contact the skin in a socket. Additionally, sweat can cause

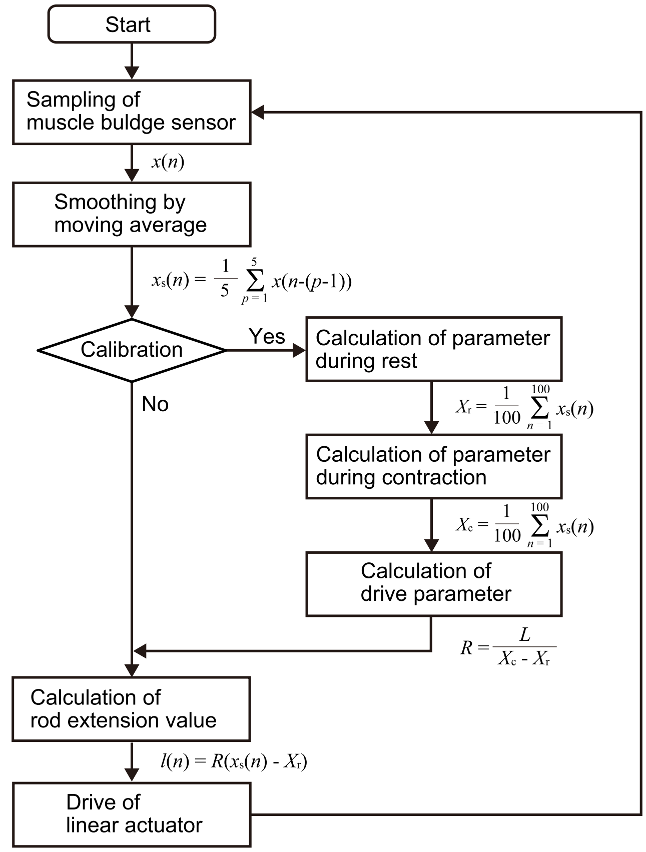

Fig. 9. Flowchart of the control system.

a short circuit between the electrodes. In contrast, the sweat problem can be reduced because the sealed muscle bulge sensor can be used through a cloth. The muscle bulge sensor can be manufactured at a low cost (about 5 USD).

The fingers open in proportion to the degree of muscle contraction, similar to the voluntary opening system in the body-powered hook. A control system is implemented in a microprocessor (Arduino Pro Mini, Sparkfun Electronics) in the body of the hand. The muscle bulge sensor is connected to it through a plug.

Fig. 9 shows the flowchart of the control system. The distance between the photoelectric sensor and the ABS resin plate is measured as a voltage value ranging from 0 V to 5 V. The voltage values are sampled at 100 Hz using a 10-bit A/D converter on the microprocessor. The n^{th} sample is defined as $x(n)$. The sampled values are smoothed by using a moving average as follows:

$$x_s(n) = \frac{1}{5}\sum_{p=1}^{5} x(n-(p-1)). \tag{1}$$

A long press on the calibration switch starts the calibration process to adapt to the user. First, the distance values at rest are acquired for 1 s by briefly pressing the switch and are averaged to determine the parameter X_r. Then, the distance values during muscle contraction are acquired for 1 s by a short pressing of the switch again and are averaged to determine the parameter X_c. Finally, both parameters are used to calculate a

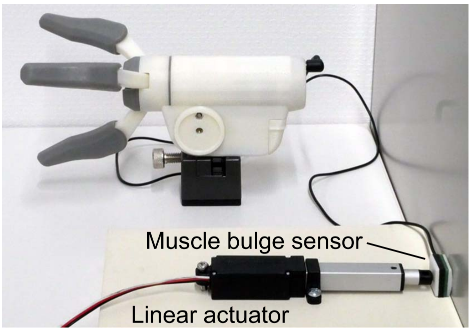

Fig. 10. Setup of the response test.

drive parameter of R as follows:

$$R = \frac{L}{X_c - X_r}, \quad (2)$$

where L denotes the maximum value of the rod extension. Since the calibration process is completed with this three-button operation, a user can perform a self-calibration.

The value of the rod extension $l(n)$ is calculated by using the drive parameter as follows:

$$l(n) = R(x_s(n) - X_r). \quad (3)$$

This value is sent to the linear servo actuator.

A short press on the calibration switch locks the movement of the fingers. In this state, a long press on the calibration switch alternately changes the mode from voluntary opening to voluntary closing. The default is voluntary opening because the user does not need to contract the muscle to hold an object.

D. Material

Plastic parts were fabricated from ABS resin using a 3D printer (Fortus 250mc, Stratasys Ltd.). The layer thickness was 0.254 mm. The joint pins and screws are made of stainless steel. The finger cap and body cap are made of silicone by injection molding.

III. Evaluation

We conducted six functional tests and user tests to verify the effectiveness of the Finch. Since the Finch is made up of many 3D-printed parts, we tested its strength and durability, which are essential for practical use.

A. Functional Test

1) Response: We examined the response of the Finch to the muscle bulge sensor press by using the setup shown in Fig. 10. The muscle bulge sensor was pressed by the rod of a linear actuator (L16-R, Actuonix Inc.) from 0 mm to 2 mm at a rate of 4 mm/s. Videos were recorded at 240 Hz to observe the movement of the fingers and the sensor and analyzed using video annotation software (Kinovea). Fig. 11 shows the relationship between the angle of the finger joint1 and the distance of the muscle bulge sensor press. The finger started to open 58 ms after the sensor was pressed. After that, the angle of the finger joint1 gradually increased and reached

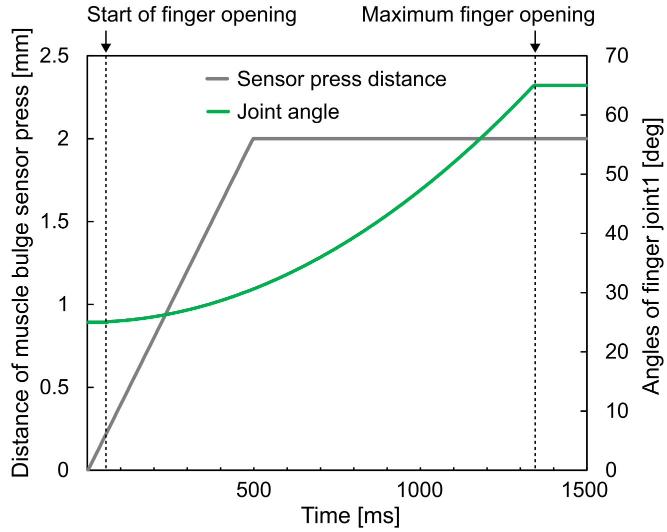

Fig. 11. Response of the Finch to the muscle bulge sensor press.

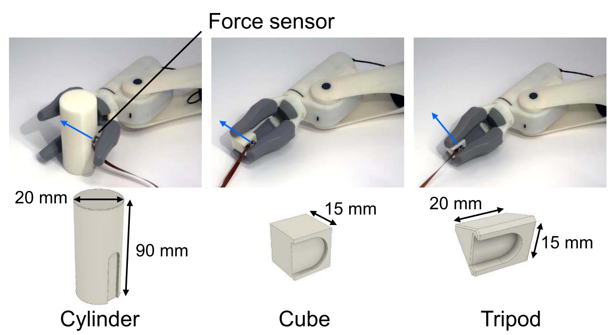

Fig. 12. Setup of the grasping force measurement with a force sensor.

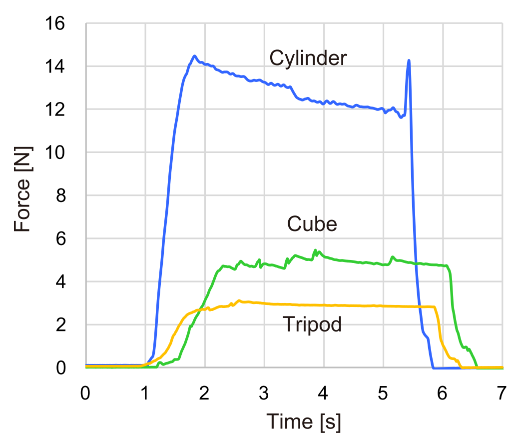

Fig. 13. Result of the grasping force measurement. The average grasping force while grasping the cylinder, small cube, and tripod was 12.8 N, 4.8 N, and 2.9 N, respectively.

its maximum at 1344 ms. The time from full depression of the sensor to the maximum opening of the finger was 847 ms.

2) Grasping Force: The grasping force was measured using a setup shown in Fig. 12. The Finch grasped three objects (cylinder, cube, and tripod) to which a force sensor (MAF-3, Wacoh-Tech Inc.) was attached. Fig. 13 shows the grasping forces while grasping each object for approximately 5 s.

Fig. 14. Examples of daily objects grasped by the Finch. When it holds stick-like objects such as a pen, the objects are supported by three fingers and a silicone body cap.

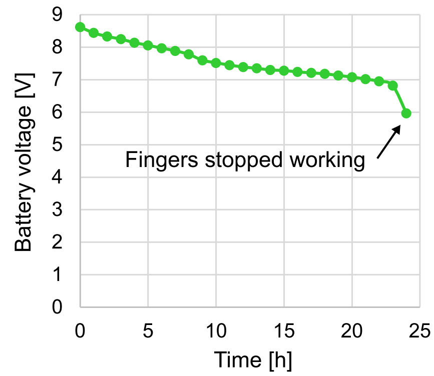

Fig. 15. Result of the battery life test.

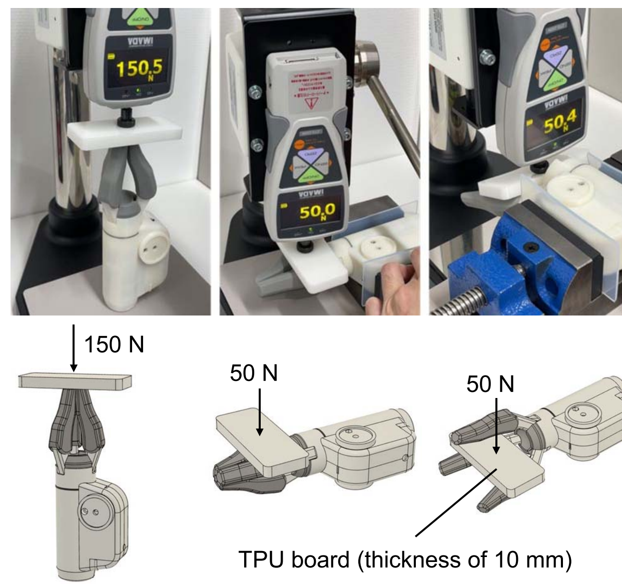

Fig. 16. Three conditions of the strength test. The load was applied to the fingers with an attachment of a force gauge.

The average grasping force while grasping a cylinder, cube, and tripod was 12.8 N, 4.8 N, and 2.9 N, respectively.

3) Daily Objects Grasping: The Finch could grasp various objects used in daily activities, as shown in Fig. 14. It could grasp fragile objects such as a tomato without crushing it and thin objects such as paper. The objects were supported with the three fingers and the silicone cylinder cap when the Finch held stick-like objects such as a spoon, fork, knife, and pen.

4) Battery Life: Battery life was tested using a lithium-ion battery (8.6 V, 800 mAh, Keenstone Corp.) under the condition that the fingers were repeatedly opened and closed every 10 seconds without load using the same setup shown in Fig. 10. Battery voltage was measured every hour. The fingers stopped working after 24 h (8640 times), as shown in Fig. 15.

5) Strength: A strength test was performed under three conditions, as shown in Fig. 16. In each condition, a load was applied to the fingers five times through a thermoplastic polyurethane (TPU) board (thickness of 10 mm) using an attachment (diameter of 10 mm) of a force gauge (ZTS-200N, Imada Co. Ltd.). No visible damage to the links and joints was observed under any condition.

6) Durability: The durability of the Finch was tested using the same setup shown in Fig. 10. The fingers were repeatedly opened and closed every two seconds without load. After 80100 grasps, the metal pin at joint1 of one finger was broken. No deformation of the sensor was observed.

B. User Test

1) Method: We conducted a Southampton Hand Assessment Procedure (SHAP) test [26], [27] with transradial amputees. The SHAP test is designed based on the analysis of grasping patterns and their frequency of use in activities of daily living (ADL). It consists of two sections: abstract object tasks and simulated ADL tasks. In the abstract object tasks, picking and placing six types of objects shown in Fig. 17(a) is performed. Each object corresponds to one of the six grasp types. Fig. 17(b) shows the six objects grasped with the Finch. The objects of each shape are made of wood and metal, as shown in Table I. The time taken to move 12 abstract objects from the rear to the front slot on the test board was recorded. Fig. 18 shows a photograph of a participant performing the abstract object tasks. The simulated ADL tasks consisted of 14 ADL tasks such as picking up coins, rotating a key, and opening/closing a zip. The time taken to complete each task was recorded. If a participant failed to complete a task within 100 s, the task was considered a failure. In the case of failure, a second trial was performed according to the SHAP test protocol.

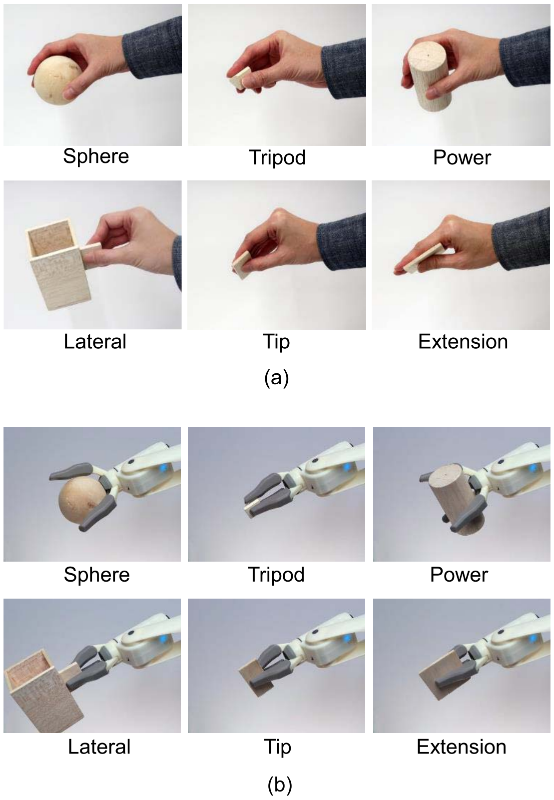

Fig. 17. (a) Six abstract objects used in the SHAP test. (b) Six objects grasped with the Finch.

TABLE I
WEIGHT OF ABSTRACT OBJECTS

Object	Weight [g]	
	Wood	Metal
Sphere	25	531
Tripod	1	21
Power	24	538
Lateral	14	229
Tip	1	71
Extension	2	143

Five transradial amputees participated in the SHAP test (five males, mean age 52.8 ± 9.4 years). Table II shows the participant's profiles. Participant A was a congenital amputee, and the others were traumatic amputees. Participant A had used the Finch for six months in his daily activities. Participant B used the Finch for one month. The other participants used it for the first time. They selected the size of the supporter by trying it on (size L or M). The muscle bulge sensor was inserted into the pocket of the supporter over the flexor carpi ulnaris, as shown in Fig. 6. The participants could wear the Finch and perform the calibration themselves. They practiced using the Finch for approximately 20 min before performing the tests.

Only participants A and B performed the simulated ADL tasks because the other participants who used the Finch for the first time had difficulty performing them. In addition, participant B also performed the SHAP test with his i-limb quantum.

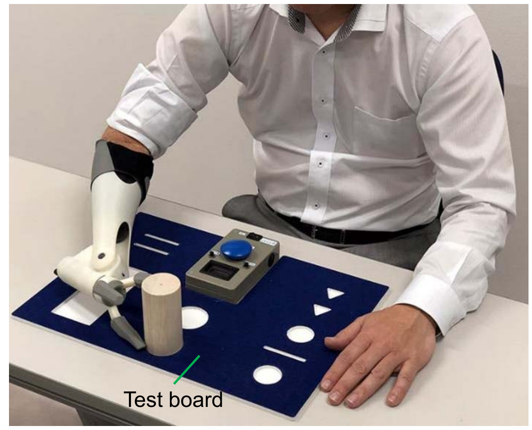

Fig. 18. Photograph of participant B performing the SHAP test.

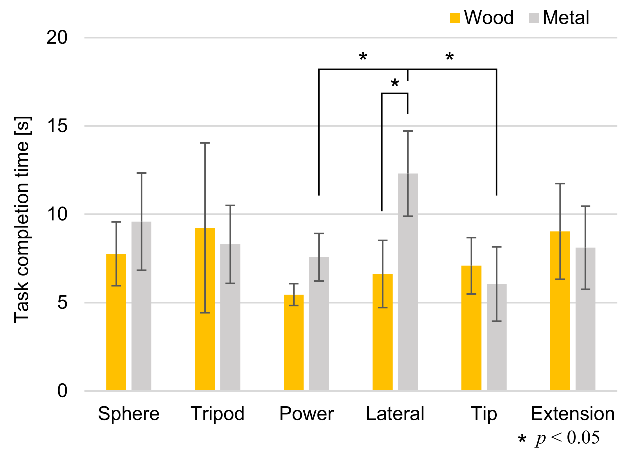

Fig. 19. Results of the abstract object tasks for the five participants using the Finch.

The ethical review board of the Osaka Institute of Technology approved the experimental protocol of this study (approval number 2018-80). Informed consent was obtained from all participants before they participated in this study.

2) Result: This study focuses primarily on the completion time of each task. The results of the abstract object tasks for the five participants are shown in Fig. 19. All participants completed all 12 tasks. The average task completion time for the five participants was less than 20 s for all tasks. The result of a two-factor ANOVA showed a significant difference only in an interaction effect ($F(5, 20) = 3.04$, $p < 0.05$). Analysis of the interaction effect showed that the task completion time of the metal object was significantly longer than that of the wooden object in the lateral task ($F(1,4) = 13.67$, $p < 0.05$). There was also a significant difference between task conditions for the metal object ($F(5, 20) = 4.74$, $p < 0.01$). Multiple comparisons showed that the completion time of the lateral task with the metal object was significantly longer than that of the power and tip tasks ($p < 0.05$). Fig. 20 shows the results of the simulated ADL tasks for participants A and B. They completed all tasks except for the glass jug pouring.

TABLE II
PARTICIPANT'S PROFILE

Participant	Age	Affected side	Stump length	Cause of amputation	Training period of Finch	Prosthesis in use
A	38	Left	90 mm	Congenital	six months	Cosmetic hand
B	48	Right	210 mm	Trauma	one month	Myoelectric hand [2]
C	63	Left	112 mm	Trauma	20 minutes	Body-powered hook [28]
D	64	Right	209 mm	Trauma	20 minutes	Body-powered hook [28]
E	50	Right	226 mm	Trauma	20 minutes	None

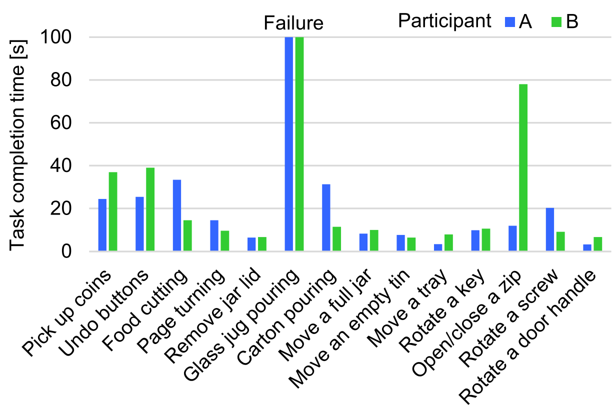

Fig. 20. Results of the simulated ADL tasks for participants A and B using the Finch.

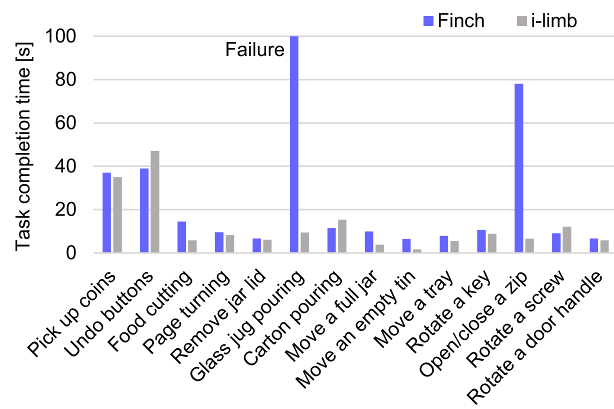

Fig. 22. Comparison of the performance with the Finch and i-limb in the simulated ADL tasks for participant B.

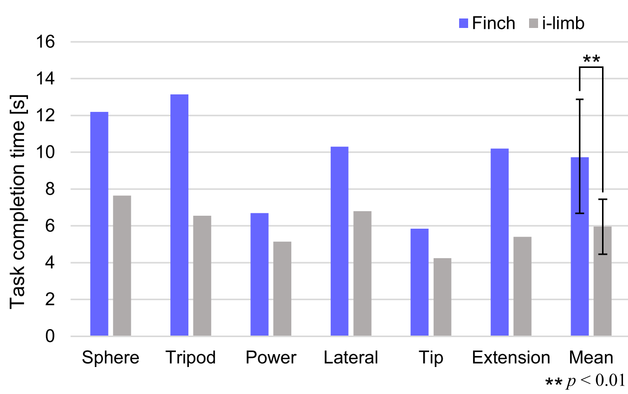

Fig. 21. Comparison of the performance with the Finch and i-limb in the abstract object tasks for participant B.

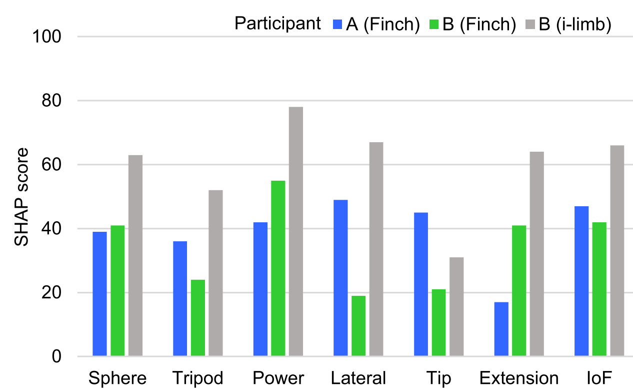

Fig. 23. SHAP scores for participants A and B.

The comparison of the performance with the Finch and i-limb in the abstract object tasks for participant B is shown in Fig. 21. Each value is the average task completion time for the wood and metal objects. The task completion time of the Finch was significantly longer than that of the i-limb (paired t-test, $p < 0.01$). Fig. 22 shows the comparison of the performance with the Finch and i-limb in the simulated ADL tasks for participant B. With the use of the i-limb, the glass jug pouring was possible.

The SHAP scores for participants A and B are shown in Fig. 23. For participant B, the scores of the Finch and i-limb are shown. The IoF (Index of Function) of participants A and B using the Finch was 47 and 42, respectively. The IoF of participant B using the i-limb was 66.

IV. DISCUSSION

Table III shows the specifications of the Finch from the functional tests. The weight of a hand with a battery was 210 g, and the total weight with a supporter socket was 330 g. The commercial anthropomorphic electric hands weigh 433–616 g (bebionic EQD: 433–616 g, Michelangelo: 510 g, i-limb Quantum: 472–558 g), and the total weight with a socket, a glove, and a battery is more than 800 g. Even the lightest prototype hand [7], which weighs 312 g, would weigh more than 700 g with a socket and battery. Compared to them, the Finch is light enough. In the user test, the participants using a myoelectric hand or a body-powered hook appreciated the lightness of the Finch. Although several single-actuator prototype hands have been proposed [29], [30], [31], they

TABLE III
SPECIFICATIONS OF THE FINCH

Weight (Hand with a battery)	210 g
Weight (Hand and socket supporter)	330 g
Recommended load	500 g
Grasping force	
Cylinder	12.8 N
Cube	4.8 N
Tripod	2.9 N
Time from close to maximum open	1.3 s
Battery life (Lithium-ion battery, 800 mAh)	24 h
Total cost	430 USD

have not been evaluated as prosthetic hands and are difficult to compare.

The hand was designed to grasp a load of 500 g, which could carry an object of 538 g in the evaluation. The grasping force when grasping a cylinder, cube, and tripod was 12.8 N, 4.8 N, and 2.9 N, respectively. It can be increased by changing the parameters of the torsional spring and the gear ratio of the linear actuator, but this would be at the expense of finger speed and strength.

In terms of battery life, under the measurement conditions of this study, the Finch could be used for 24 h, which is sufficient for daily use. Since durability can be an issue for 3D-printed prosthetic hands, we investigated the durability of the Finch and found it to be durable enough. The total cost of materials and parts was approximately 430 USD. As a practical prosthetic arm, its cost is low.

The response delay to the muscle bulge sensor press was 58 ms. Although there was no general response delay data for myoelectric hands, the SensorHand Speed [32] was about 20 ms. The response delay of the Finch is due to the phase delay caused by the moving average and the responsiveness of the linear actuator. Since the moving average is calculated from five points, the number of points could be reduced. However, a delay of 58 ms may not be a problem because it has been reported that a controller delay of more than 100 ms can degrade performance [33]. In fact, there were no comments on the responsiveness of the Finch from the participants in the SHAP test.

The time from the start of finger opening to full opening was 1344 ms, which was longer than the values of the commercial prosthetic hands (Michelangelo: 330 ms, i-limb: 800 ms, System Electric Hand Digital Twin: 900 ms, bebionic: 1000 ms). This time was due to the actuator speed of 6.5 mm/s. This speed can be improved by changing the gear ratio, but at the expense of grasping force. There were no comments on the speed of the Finch from the participants as with the responsiveness. The user may not care about the speed if he or she does not open the fingers wide and often in voluntary opening mode.

The five participants completed all 12 abstract object tasks in the user test. For the lateral task, the task completion time for the metal object was significantly longer than that for the wooden object. The completion time of the lateral task with the metal object was significantly longer than that of the power and tip tasks. Since the metal object in the lateral task weighed more than 200 g, and the participants had to grasp the slippery handle away from the object's center of gravity, the task was difficult for the participants.

The two participants performed the simulated ADL tasks and completed all 13 tasks except the glass jug pouring task. However, the participants had difficulty with the tasks that required grasping force with the fingers almost closed, such as food cutting, rotating a key, and opening/closing a zip, due to the low stiffness of the fingers. For the same reason, they could not complete the glass jug pouring. The stiffness of the fingers should be improved.

The IoF of the SHAP test for the two participants was 44 and 47. Since each task is performed once, the performance of one trial has a significant effect on the IoF. For a more accurate evaluation, multiple trials or an Assessment of Capacity for Myoelectric Control (ACMC) would be required. We would like to focus on the results that two amputees with some familiarity with the Finch could successfully perform 25 tasks in the SHAP test.

The muscle bulge control system allowed the participants to control the Finch intuitively. The participants could perform the calibration themselves and learn the relationship between their muscle bulge and the finger opening of the Finch. However, for the tasks lifting heavy objects, such as the sphere task, the fingers opened unintentionally in a few cases. This unintentional opening of the fingers is due to muscle contraction when lifting heavy objects and is a problem that should be improved in the future.

The supporter socket made it possible to use the Finch on the same day without taking a mold of the user's stump beforehand. Since the muscle bulge sensor was inserted into the pocket of the supporter, no additional processing on the socket was required. With conventional myoelectric sensors, sweat causes discomfort and skin irritation because the metal electrodes directly contact the skin in a socket. In addition, sweat might cause a short circuit between the electrodes. In contrast, the sweat problem can be reduced because the sealed muscle bulge sensor can be used through a supporter. The supporter socket did not slip through the short stump of participants A and C.

When comparing the Finch and i-limb for participant B, the performance of the i-limb was superior to that of the Finch. The reasons are the stiffness of the i-limb, his experience with the i-limb, and the dexterous grasping with five fingers. Since this is a preliminary evaluation using the i-limb, comparisons with other myoelectric hands should be necessary. However, considering the differences in the weight, cost, and comfort of the socket between the Finch and i-limb, the Finch can be an alternative for users who find the grasping function of the Finch sufficient.

Amputees may not prefer the appearance of the Finch because it is a non-anthropomorphic prosthetic arm. However, since we think of the Finch as a tool like scissors, it is possible to use it only when working. Conventional myoelectric hands

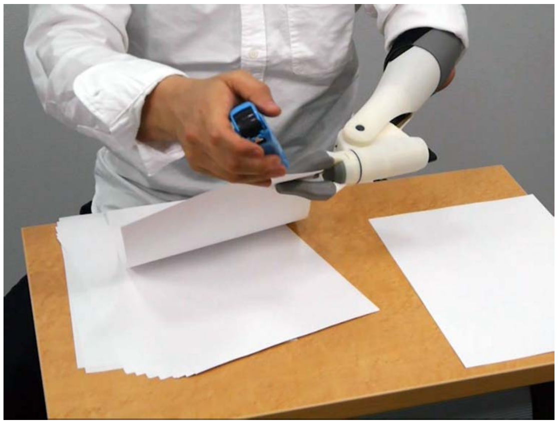

Fig. 24. Photograph of participant A stapling documents with the Finch.

are difficult to use in this way, but the Finch, which is lightweight and easy to wear and use, makes this possible. For example, participant A carries the Finch in his bag and uses it only when working, as shown in Fig. 24.

V. Conclusion

We reported on the prosthetic arm termed "Finch." The hand with three opposing fingers and the muscle bulge control system allowed amputees to grasp various objects. The supporter socket allowed easy wear. A simple design using a linear actuator and 3D-printed parts achieved light weight (330 g) and low cost (430 USD). Six functional tests and user tests using SHAP showed that the Finch had a practical function that could be used in daily activities.

In a future study, we plan to develop a more compact and lightweight Finch for children with forearm deficiency.

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