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Paper:

Realistic and Highly Functional Pediatric Externally Powered Prosthetic Hand Using Pneumatic Soft Actuators

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It is known that introducing a pediatric externally powered prosthetic hand from an early age has certain merits such as the recovery of body image. However, this process is not popular in Japan. The high cost and technological problems of the hand have resulted in difficulty in its popularization. The pediatric prosthetic hand must be lighter and smaller than the adult one. Furthermore, parents of users prefer a prosthetic hand, such as a human arm and hand. We developed a prosthetic hand that demonstrates certain functionalities and appearances similar to a real human hand. The prosthetic hand consists of miniature McKibben actuators and is manufactured from acrylonitrile-butadiene-styrene resin and covered by a silicon glove. It has flexible joint structures and can grasp objects of various shapes. In this paper, we present a prototype of the pediatric prosthetic hand and the results of gripping experiments, bending and extension of finger experiments, and user tests.

Keywords: prosthetic hand, soft actuator, McKibben, silicone rubber, soft robotics

1. Introduction

The factors contributing to limb deficiency in children primarily include congenital deficiencies, trauma, and tumors. The frequency of congenital limb deficiency was reported to be approximately six cases per 10,000 births [1]. The number of births in Japan in 2018 was approximately 920,000. On the basis of these numerical values, it is estimated that approximately 550 children with deficiencies in their limbs are born annually in Japan. While a deficiency that occurs in fingers is the most common congenital limb deficiency, there is minimal information available on the importance of using powered prosthetic hands; consequently, it is difficult for rehabilitation staff and users to obtain information on the scope and type of application and the flow of supply in the powered prosthetic hands. In the actual situation in the field of rehabilitation, there are not many cases that require the mounting of limb prostheses for the purpose of handedness exchange, which is a process that shifts the handedness from one hand to the other when the function of handedness is lost; consequently, it is less likely for society to notice such a situation.

In addition to these situations, the problems of cost, proficiency, and equipment are considered as the factors owing to which the powered prosthetic hands for children are not widespread. More specifically, in terms of cost, the examination standard for public support is set higher in Japan when compared to Western countries; consequently, a myoelectric prosthetic hand is expensive. In terms of proficiency, the number of training facilities for the myoelectric prosthetic hand is limited; moreover, in terms of equipment, there are technical problems such as the necessity of reduction in size and weight. In Western countries, public support is generous, and patient support systems by private groups are also satisfactory. Currently, all upper limb prostheses in Japan are imported products. Consequently, the purchase of the upper limb prosthesis costs as much as 1.5 million Japanese yen, which is a considerable financial burden for child users who are required to change upper limb prostheses in accordance with the growth. Therefore, to improve the quality of life (QOL) of child users, it is important to provide users with more options in the use of upper limb prostheses by improving the support systems, developing domestic upper limb prostheses for children, and providing an inexpensive and stable supply. It is considered that an increase in requirements will facilitate the improvement of training facilities and support systems.

Conversely, the advantage of prescribing powered prosthetic hands for children from the early stage is that the usage opportunity of the unilateral arm side can be increased, thereby leading to reinforcement of muscle strength. In addition, cultivating the habit of using the powered prosthetic hand from an early stage will also lead to the recovery of the body image pertaining to the unilateral arm side; further, the powered prosthetic hand can be used as a part of the body after the growth of the user. In unilateral transverse partial hemimelia, owing to the difference in the weight between the healthy upper limb and the unilateral arm, secondary problems such as scoliosis will be generated. Therefore, an improvement in body balance can also be expected by appropriately prescribing the powered prosthetic hand from an early stage as the weight of the non-unilateral arm becomes similar to that of the unilateral arm. In addition, when a cosmetic upper limb prosthesis is used, it only allows the user to press objects, and the user tends not to utilize the space on the mounting side.

On the basis of this background, we developed a powered prosthetic forearm for children that solves the cost and technical problems of the upper limb prosthesis. Our final target is a powered prosthetic hand for children that can achieve an equivalent performance to the Electric Hand 2000 (which has a weight of 130 g for the prosthetic hand alone), manufactured by Ottobock Co., Germany, which is the most extensively used powered prosthetic hand for children. In addition, we aim to improve the QOL with an expanded activity region by providing an upper limb prosthesis that enables the user to perform actions such as grasping a 500 mL plastic bottle and putting on and taking off trousers, which are required for the everyday functioning of children.

Our research group developed a powered prosthetic hand for children using a shape memory alloy [2–4]. This prosthetic hand drives each unit by using a shape memory alloy actuator (and not a motor), which has the characteristics of silent driving, easy reduction in size, and high output. It is designed to be covered with cosmetic gloves for six-year-old children and the primary components of the body were produced using polyacetal resin to facilitate weight reduction and processing. The body weight is 139 g, including the forearm. However, this model demonstrated the problem of a low responsivity time of 4.3 s in the opening motion and 2.3 s in the closing motion in the finger opening and closing experiment.

To address these issues, we propose a new powered prosthetic forearm for children with a modified prosthetic structure using a miniature McKibben pneumatic artificial muscle as the actuator in the prosthetic hand. Although several powered prosthetic hands are being practically used, users are not necessarily satisfied. For example, despite the fact that the opening and closing times of a myoelectric hand prosthesis for adults (System Electric Hand Digital Twin: 8E38; Ottobock Co.) are 0.9 s, the users have complained that its opening and closing speed is slow. This is because the users want a motion equivalent to healthy hands and desire a utilization that is free from any discordance with their intentions to the maximum possible extent. Thus, to solve the problem of the opening and closing speeds, a miniature McKibben pneumatic artificial muscle with quick response was used as an actuator. The commercially available upper limb prostheses use a grasping mechanism with a motor and gear; this results in a case where the driving noise and finger movement can result in undesirable actions such as shaking hands, which can scare people. In contrast, the artificial muscle does not generate any noise during the operation. In addition, the artificial muscle has an air spring; consequently, it has the advantage that, during a handshaking operation, it will not shake a human hand too strongly; hence, it will not cause fear in people while shaking hands with the user.

This article first describes the actuator of a powered prosthetic forearm for children. Then, it explains the prosthetic hand, Version 1, which is the first prototype, in terms of its structure, the drive principle of the finger, and the grasping test. Next, this article explains the structure and basic characteristics of the prosthetic hand, Version 2, which is the improved second prototype to overcome the problems of the prosthetic hand, Version 1. Finally, this paper discusses the gripping forces of both prosthetic hands, opening and closing times of fingers, and user test results, and verifies the adaptability of these prosthetic hands.

2. Pediatric Externally Powered Prosthetic Hands

2.1. Related Works

Research on prosthetic hands has been conducted by several researchers [5–8]. These studies are development examples of upper limb prostheses for adults. Conventional myoelectric prosthetic hands are required to have a high gripping force and durability; hence, many of them were made of metal. However, as the prosthetic hands for children are required to be small in size and lightweight, it is assumed that a prosthetic hand made of metal will increase the weight and impose a burden on the user. Consequently, the prosthetic hands for children have advanced in terms of the utilization of resin, which is lighter than metal. The recent popularization of 3D printers has resulted in the production of lightweight components with complicated shapes at low prices. As an inexpensive prosthetic hand for children manufactured by using a 3D printer, Kobayashi et al. [9] proposed the development of a "small Finch," which is obtained by reducing the size and weight of an electric hand prosthesis for adults called Finch. With a simple structure in which a single linear actuator opens and closes three fingers, the small Finch is reduced in size and weight; thus, including the socket part, it weighs approximately 270 g. Because it is composed of 3D printed and general-purpose components, it can be produced inexpensively at less than 50,000 Japanese Yen. In addition, Hirai et al. [10] proposed a myoelectric prosthetic hand for children with a wire-driven mechanism to achieve a balance between weight reduction and gripping force. They produced two types of prosthetic hands with different wire tension maintenance mechanisms and com-

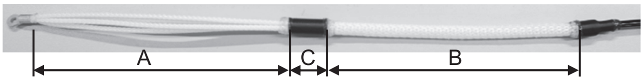

Fig. 1. Assembled miniature McKibben actuator.

pared and examined the gripping force. The difference between these existing studies and our research lies in the structure of the finger. Further details are presented in Section 3.

2.2. Miniature McKibben Pneumatic Artificial Muscle

This section describes a miniature McKibben pneumatic artificial muscle, which is an actuator for the prosthetic hands for children that are proposed in this study. In the miniature McKibben pneumatic artificial muscle, the circumference of a thin silicone rubber tube is covered with a sleeve of a woven fiber layer. By applying air pressure from the air supply tube, it expands in the radial direction and performs a contraction motion in the axial direction. The miniature McKibben pneumatic artificial muscle has excellent compliance properties, can be flexibly bent, has a high shape adaptability, and is lightweight. However, the actuator is so thin that the contraction force is low. Therefore, as illustrated in **Fig. 1**, we produced an actuator unit for use with the prosthetic hand by combining the miniature McKibben pneumatic artificial muscles with different diameters. More specifically, the actuator unit was produced at a total length of 200 mm, consisting of three parts: part A (in **Fig. 1**) consists of three artificial muscles of 2 mm outside diameter bundled to a length of 90 mm, part B, which is an artificial muscle of 4.8 mm outside diameter and length of 90 mm, and part C with a length of 20 mm, which is the connecting part. The contraction amount and generation force of the actuator unit are subsequently explained. We measured the contraction amount 24 times with an applied pressure of 300 kPa, and calculated the average value and standard deviation. We measured the generation force three times with an applied pressure of 300 kPa and calculated the average value. Thus, an average contraction amount of 30.3 mm and a standard deviation of 0.25 mm were measured. The average generation force was 18.7 N.

2.3. Powered Prosthetic Hand, Version 1

Figure 2 shows an overview of the first version of the prosthetic hand. The prosthetic hand, Version 1, is used by wearing a cosmetic glove made of silicone rubber. In the forearm part, only a manifold for branching the air is incorporated, and the prosthetic hand is shaped approximately similar to the human arm. The prosthetic hand weighs 267 g, which is inclusive of the glove, the actuator unit arranged on each finger, and a piping tube. **Fig. 3** illustrates the structure of the four fingers (i.e., the fingers other than the thumb) from the index finger to the little finger. The inside of the finger is a cavity, in which the actuator unit is arranged. Two silicone rubber rods of 3 mm diameter were used for the finger joint, to which an exoskeleton component of the finger was connected. The use of the silicone rubber rod in the finger joint part provides a structure where the joint part deforms to release the force when it is received in a direction other than the flexion and extension directions owing to an external factor.

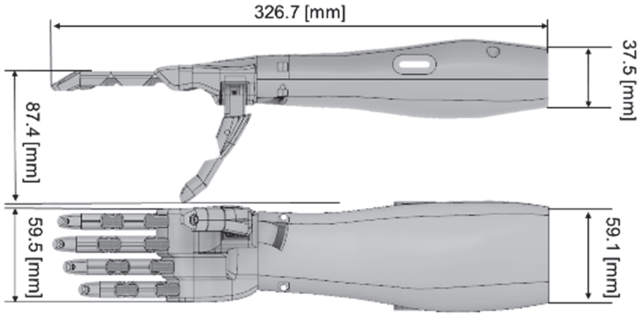

Fig. 2. Overall view of the prosthetic hand, Version 1.

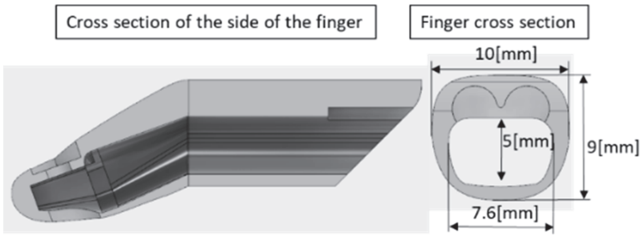

Fig. 3. Structure of artificial finger.

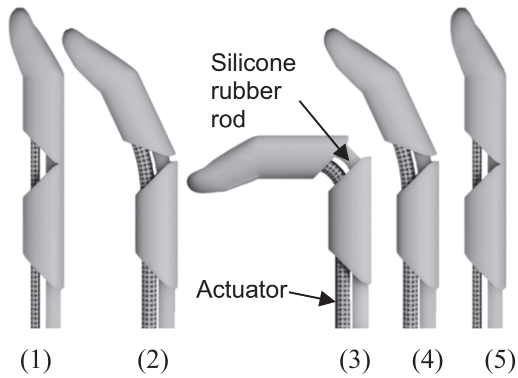

Fig. 4. Driving principle of artificial finger.

The finger flexes by the contraction of the actuator and extends by the tension of the silicone rubber rod used for the joint part. **Fig. 4** illustrates the principle of flexion and extension of the finger. In **Fig. 4(1)**, the actuator does not move and the finger is extended. When air pressure is applied to the actuator, the actuator expands in the radial direction and contracts in the axial direction (**Fig. 4(2)**). Consequently, the finger joint flexes as shown in **Fig. 4(3)**. When the applied pressure to the actuator is reduced, the actuator extends (**Fig. 4(4)**), and the finger returns to the extended state by the tension of the silicone rubber rod of the joint (**Fig. 4(5)**).

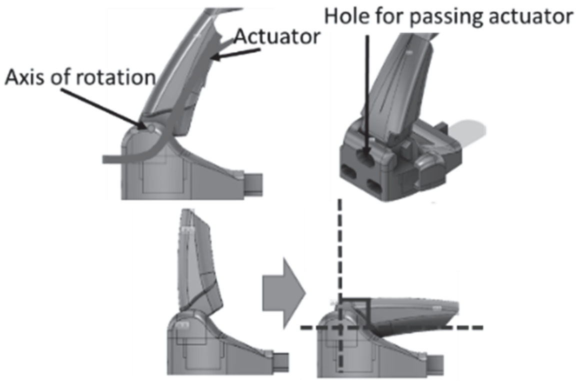

Fig. 5. Thumb CM joint with changed drive direction.

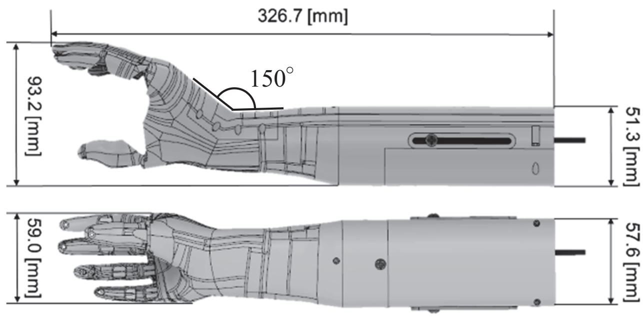

Fig. 6. Overall view of the prosthetic hand, Version 2.

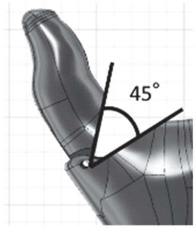

Fig. 7. The joint of the thumb.

Next, the structure of the thumb is explained. In the prosthetic hand, Version 1, the orientation of the axis of the carpometacarpal (CM) joint of the thumb was rotated by 90° to drive the thumb CM joint in the direction where it is grasped with respect to the palm. The joint part was configured to flex by the contraction force of the actuator and extend by the tension of the glove. In addition, the CM joint part used an aluminum shaft of 2 mm in diameter and is designed such that it can flex by 90° from the extension state. **Fig. 5** illustrates the designed thumb CM joint part.

The metacarpophalangeal (MP) joint of the thumb was produced by a shaft connection using an aluminum shaft. This prevents the joint part from twisting owing to an external force. The MP joint part was designed such that it can flex by 70° from the extension state; moreover, the drive is limited so that the finger cannot bend outward from the extension direction.

In the measurement of the graspable mass, we fixed the prosthetic hand to achieve a uniform grasping motion, and measured the length of time for which plastic bottles with varying weights were grasped. The pressure applied from the compressor in the experiment was 300 kPa; moreover, tap water was placed in a beverage plastic bottle of 86 mm diameter. The amount of tap water was increased by 10 g from an initial weight of 430 g. We completed the measurement when the duration of grasping time of the plastic bottle had elapsed, which was 10 s. We conducted the measurement 10 times and calculated the average grasping time. Thus, it was determined that the average grasping time was 10 s up to a mass of 480 g. However, it became 9.4 s for 490 g, 7 s for 500 g, and the bottle could not be grasped when it weighed 510 g or more.

2.4. Powered Prosthetic Hand, Version 2

The prosthetic hand, Version 1, was unable to perform stable grasping of a plastic bottle with a weight of more than 490 g; thus, we considered that further improvement in the grasping ability was required. Therefore, we designed a second version of the prosthetic hand in which the structure from the palm part to the finger and forearm part of the prosthetic hand, Version 1, were changed.

Figure 6 illustrates the overview of the prosthetic hand, Version 2, including the forearm part. Each component of the finger, palm, wrist, and forearm of the prosthetic hand, Version 2, was designed using available data and a 3D scanner measured the shape of the mold used for producing the glove. Thus, the dimensions matched the glove and a large space for arranging the actuator unit was ensured. In the inside of the palm, a division was provided by three walls so that an artificial muscle unit could be arranged with branches to the five fingers. The wrist is in a standard state of extension of approximately 30°. This is for preventing the thumb from interfering with clothing when the hand with the attached prosthetic hand is lowered naturally when the hand is parallel to the forearm. The weight of this prosthetic hand is 226 g, including the glove, actuator units arranged on each finger, and piping tube; thus, the weight was successfully reduced by 41 g when compared to the prosthetic hand, Version 1.

The thumb of the prosthetic hand, Version 2, was configured to be movable only at the MP joint part and was axially connected by an aluminum shaft of 2 mm diameter. **Fig. 7** illustrates the joint structure of the thumb. The MP joint has an angle of range of motion of 45°. Next, we discuss the finger joint structure from the index finger to the little finger in which the proximal interphalangeal (PIP) and MP joints are movable. A silicone rubber rod is used for the joint connection. **Fig. 8** illustrates the PIP and MP joint structures for the four fingers from the index finger to the little finger and **Table 1** lists the angle of the range of motion of each finger. The angles of the ranges of motion of these fingers were determined to ensure that a cylindrical material with a minimum diameter of 20 mm could be grasped with grip strength.

Next, the pressing force of each finger is explained.

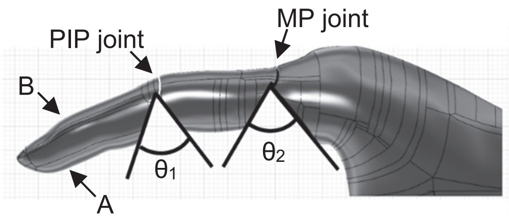

Fig. 8. The joint of the finger exclude thumb.

Table 1. The range of motion in the joint of fingers.

Type of finger	θ_1 [°]	θ_2 [°]
Index finger	60	70
Middle finger	60	70
Ring finger	55	60
Little finger	55	60

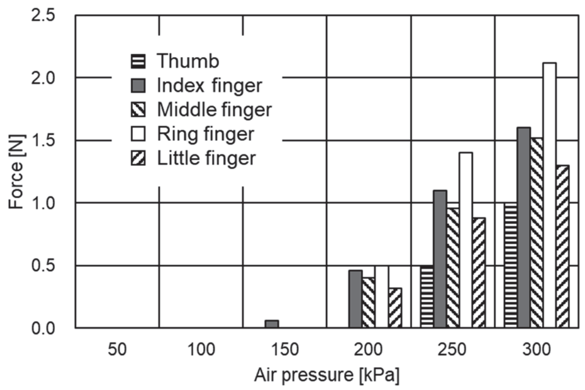

Fig. 9. The force of each finger.

The pressing force was measured by mounting a cosmetic silicone rubber glove to the prosthetic hand and placing a force gauge on the inside of the fingertip (point A in **Fig. 8**), and changing the applied pressure to the actuator. **Fig. 9** illustrates the measurement results of the pressing force. When the applied pressure was 150 kPa or less, the pressing force could not be measured in most fingers. This implies that the fingers are not driven. Although there was a difference in the pressing force among the fingers, a pressing force of 1–2 N was obtained in all fingers at 300 kPa.

The stiffness of each finger, except the thumb, is subsequently explained. The stiffness of the fingers presented here is the hardness of each finger at the MP joint. The repulsive force from the finger was measured by mounting the cosmetic silicone rubber glove on the prosthetic hand, positioning the force gauge on the outside (point B in **Fig. 8**) of the fingertip, and varying the joint angle (θ_2 in **Fig. 8**) of the MP joint. At this time, the joint angle (θ_1 in **Fig. 8**) of the PIP joint was fixed at each value listed in **Table 1**. Through this experiment, the linearity was determined at the measured value, and thus the stiffness k [mN/°] and correction value b [mN] were calculated by the linear approximation of the linear function. **Table 2** lists the stiffness and correction values for each finger. These results indicate that the repulsive force is 1 N or less even at the maximum bending angle of the MP joint.

Table 2. The stiffness of MP joint of fingers.

Type of finger	k [mN/°]	b [mN]
Index finger	17.6	−0.24
Middle finger	9.6	−0.05
Ring finger	6.6	0.17
Little finger	13.0	−0.01

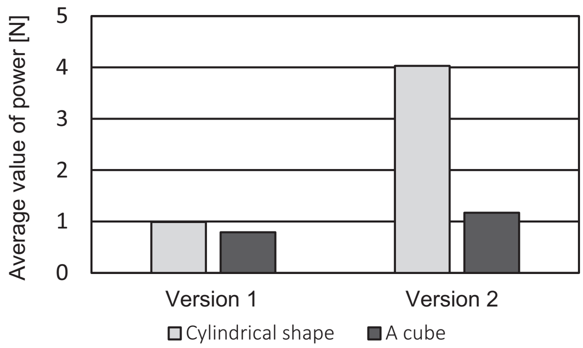

Fig. 10. Average value of power each prosthesis hands.

3. Experimental Results of the Prosthetic Hand

3.1. Gripping Force

We measured the fingertip generation force using a pressure sensor, and compared the grasping ability of the prosthetic hands, Versions 1 and 2. In the measurement experiment for the generation force at the fingertip, the applied pressure was 300 kPa. As a target object to be grasped by the gripping force, a cylinder of 40 mm diameter and 100 mm height was prepared, and a pressure sensor was attached to the side surface of the cylinder. As a target object to be precisely grasped, a cube of 15 mm length was prepared, and a pressure sensor was attached to one surface. At the time of measurement, the target object was grasped so that the inside of the fingertip of the thumb of the prosthetic hand came into contact with the pressure sensor. We calculated and compared the average of the numerical values obtained during five measurements. **Fig. 10** illustrates a graph of the average generation force of each prosthetic hand. The prosthetic hand, Version 1, demonstrated an average generation force of grasping by a gripping force of 0.99 N and average generation force of precise grasping of 0.79 N. The prosthetic hand, Version 2, demonstrated an average generation force of grasping by a gripping force of 4.03 N and average generation force of precise grasping of 1.17 N. The measurement results indicated that the prosthetic hand, Version 2,

Table 3. Bending and Extending of motion in the joint of fingers.

Model	Bending time [s]	Extending time [s]
SMA hand	2.3	4.3
Proposed hand Ver.1	1.1	1.2
Proposed hand Ver.2	0.4	0.5

has a generation force that is approximately 4.1 times greater for grasping using the gripping force (grasping of the cylinder) and approximately 1.5 times greater for precise grasping (grasping of a regular hexahedron) when compared to the prosthetic hand, Version 1.

3.2. Bending and Extending of Finger

This section explains the opening and closing times of the fingers of the prosthetic hands, Version 1 and 2. Each prosthetic hand was mounted with a cosmetic silicone rubber glove and operated with 300 kPa of applied air pressure of the actuator. At this time, the duration of time until the thumb and index finger flexed and came in contact was measured as the closing time. The drive of the actuator was stopped, and the duration of time until the thumb and index finger were extended and stopped by the resilience of the glove and joint was measured as the opening time. **Table 3** lists the measurement results and the functioning of our prosthetic hand was compared with the opening and closing times of the fingers of a prosthetic hand for children (SMA hand) that uses the shape memory alloy developed by this research group.

The results of the experiment indicate that the opening and closing times of the fingers of the prosthetic hand, Version 2, were the fastest, where the closing time of the finger was 0.4 s and the opening time was 0.5 s. The opening and closing times of the commercially available general powered prosthetic hand (System Electric Hand Digital Twin: 8E38; Ottobock Co.) are both 0.9 s. Thus, the prosthetic hand, Version 2, operates more smoothly than the commercially available powered prosthetic hand.

3.3. User Tests

A grasping experiment was conducted in which the prosthetic hands, Versions 1 and 2, were operated by a myoelectric signal for five healthy males in their twenties and one twelve-year-old female child. This experiment was conducted with the approval of the Life Science Experiment Ethics Committee of the Osaka Institute of Technology (Approval Number 2019-17). In this experiment, a prosthetic hand was attached to a healthy upper limb through a harness. For air supply, a desktop-type compressor (model number: DPP-ATAD, maximum discharge flow rate: 2.0 L/min (at 0.5 MPa), maximum discharge pressure: 0.55 MPa, mass: 4.1 kg) by Koganei Corporation was used, and the applied pressure to the actuator was set to 300 kPa.

This myoelectric system is composed of a PC (for power supply), microcomputer (Arduino), drive circuit of a solenoid valve, and myoelectric sensor. We used MyoWare myoelectric sensor, manufactured by Advancer Technologies, LLC. This sensor has an electrode mounted directly on the substrate, and it can be mounted on the body by attaching a biosensor pad for performing myoelectric measurement. The myoelectric sensor reads the myoelectric value of the test subject, and Arduino discriminates the myoelectric value. Subsequently, the opening and closing motions of the solenoid valve connected to the actuator built in the prosthetic hand are controlled in accordance with the output signal of the Arduino, thereby achieving the grasping and releasing operation of the prosthetic hand. The muscles used for myoelectric control are the flexor carpi and extensor carpi muscles. We adopted a method in which the opening and closing motions of the prosthetic hand and the state of the prosthetic hand are maintained by using the myoelectricity of these two muscles. That is, the palmar flexion motion of the wrist raises the myoelectric value of the flexor carpi muscle, and the dorsal flexion motion of the wrist raises the myoelectric value of the extensor carpi muscle. Then, we caused the palmar flexion motion to correspond to the closing motion of the prosthetic hand and the dorsal flexion motion to correspond to the opening motion of the prosthetic hand, and ensured that the state of the prosthetic hand was maintained when neither motion was performed.

The processing method of the myoelectric value includes averaging and low-pass processing of the myoelectric values of the flexor carpi and extensor carpi muscles; then, the difference between the two myoelectric values is calculated and a threshold value is provided to the derived value, thereby controlling the opening and closing motion of the prosthetic hand.

Using Shapley additive explanations (SHAP) approach [a] as an evaluation instrument, we measured the length of time required for object movement. Metal and wooden objects in six different shapes were utilized in the experiment. The duration of time from the moment at which the prosthetic hand came in contact with the target object to the moment at which the finger of the prosthetic hand separated from the target object was set to be the required time; moreover, we judged that a shorter required time indicated a superior result.

Figures 11 and **12** illustrate the measurement results of a healthy male in his twenties. **Fig. 11** shows the results using a wooden object and **Fig. 12** illustrates the results using a metal object. For wooden objects, the prosthetic hand, Version 2, was able to move four out of the six types of objects in a shorter time. However, there was not much difference in the required time, and both versions of the prosthetic hand were able to move most of the objects within 5 s, thereby suggesting that a smooth operation was successfully performed. This indicates that if the mass of the object is light (25 g for the heaviest sphere) and the ob-

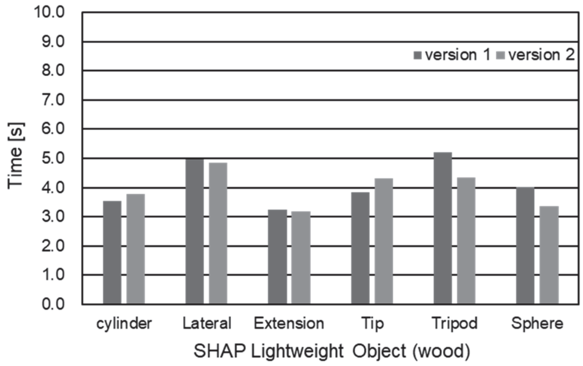

Fig. 11. The results of SHAP test with lightweight object (wood) by a man in his twenties.

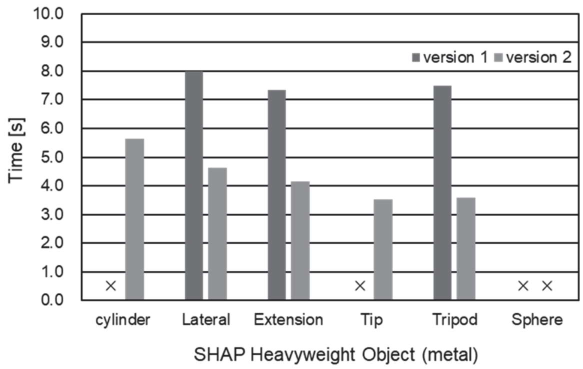

Fig. 12. The results of SHAP test with lightweight object (metal) by a man in his twenties.

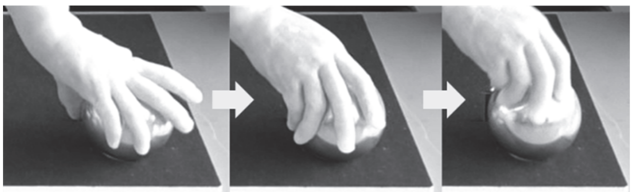

Fig. 13. SHAP test with lightweight object (metal) by a man in.

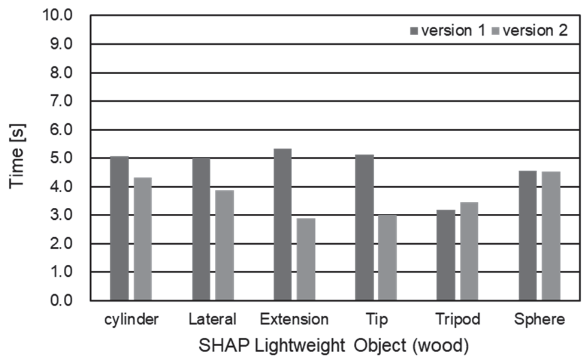

Fig. 14. The results of SHAP test with lightweight object (wood) by 12-years-old girl.

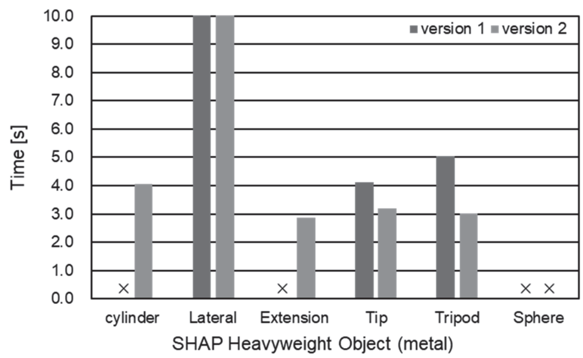

Fig. 15. The results of SHAP test with lightweight object (metal) by 12-years-old girl.

ject can be grasped, both versions of the prosthetic hands are able to move the object.

Next, while considering the metal objects, the prosthetic hand, Version 1, could not move the cylinder, small plate (tip), and sphere, whereas the prosthetic hand, Version 2, could not move the sphere. In addition, there was a difference in the movement time among the objects that could be moved. This is because the mass of metal objects is heavier than that of wooden objects (538 g for the heaviest cylinder), and the inability to move them is considered to be caused by the insufficient grasping force of the prosthetic hand. **Fig. 13** illustrates a scene where a sphere is grasped using the prosthetic hand, Version 2. As illustrated in **Fig. 13**, it is determined that the prosthetic hand was so small with respect to the metal sphere that the finger could not be bent sufficiently, and thus the grasping force did not act on the object.

Next, let us consider the measurement results obtained for five males in their twenties. Out of the 60 items (12 types of objects $\times$ five subjects), the total number of items that could be moved in a shorter duration of time by the prosthetic hand, Version 2, and the items that could be moved only by the prosthetic hand, Version 2, were 45 items. Therefore, we obtained the result that the prosthetic hand, Version 2, is 75% superior to the prosthetic hand, Version 1. However, the prosthetic hand, Version 2, required more time to move the nine objects when compared to the prosthetic hand, Version 1; moreover, it was not possible for both versions of the prosthetic hands to grasp approximately six items. In the case of the nine items that required more time for movement by the prosthetic hand, Version 2, there were certain experiment participants whose myoelectric signals were easy to detect, and certain experiment participants whose myoelectric signals were difficult to detect. Therefore, it is considered to be because of not only the problem of the grasping force of the prosthetic hand but also the fact that the prosthetic hand could not be operated as expected by the myoelectric system.

We conducted a similar experiment with a child. **Figs. 14** and **15** illustrate the measurement results of a 12-year-old girl. **Fig. 14** shows the results for grasping of wooden objects and **Fig. 15** shows the results for grasping of metal objects. For wooden objects, the prosthetic hand, Version 2, was able to move five out of the six types

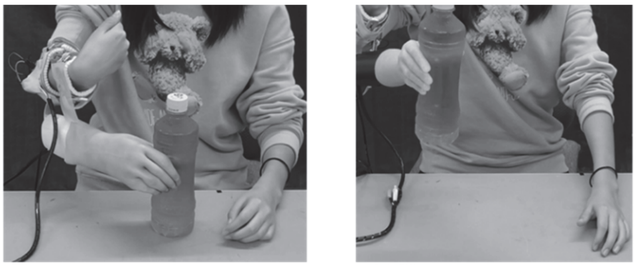

Fig. 16. Operating the developed hand by 12-years-old girl.

of objects in a shorter length of time. Moreover, similar to the results obtained in the case of adult male participants, both prosthetic hands were able to move most of the objects in 5 s or less. Therefore, it is considered that a smooth operation is possible. Next, for metal objects, the prosthetic hand, Version 1, could not move the cylinder, large plate (extension), and sphere, while the prosthetic hand, Version 2, could not move the sphere. In addition, for the box-like object (lateral), both prosthetic hands took 10 s or more to move the object. This is due to not only the insufficient grasping force of the prosthetic hand but also the influence of the instability of the motion by the myoelectric operation. We confirmed that the myoelectric signal was more difficult to detect in the child than in the adult males.

Figure 16 illustrates a scene of the grasping experiment of a plastic bottle by the girl child. The plastic bottle was an unopened bottle of 500 mL with dew condensation generated on the surface of the plastic bottle as it had been cooled in a refrigerator in advance. In the experiment, we asked the child to perform the motion of grasping the plastic bottle and lifting it to a height of 20 cm or more. From the experiment, it was determined that she could not lift the plastic bottle using the prosthetic hand, Version 1, as illustrated in the figure on the left in **Fig. 16**. This failure in grasping was caused by the fact that the plastic bottle was heavy, and the fingers could not grasp the plastic bottle because the fingers slipped owing to the dew condensation. However, stable grasping was possible using the prosthetic hand, Version 2. It is considered that the reinforcement of the grasping force and improvement of the finger structure affected the success of grasping.

In addition, to evaluate both versions of the prosthetic hand, a questionnaire was presented to the participants. One of the comments obtained was that even participants who were using the prosthetic hand for the first time were able to easily operate it. It is considered that as the operation process is as simple as opening and closing the fingers of the prosthetic hand only by pressurization and depressurization of the air pressure in the tube, it is intuitively easy to operate. In addition, it was evaluated that the prosthetic hand, Version 2, could grasp more articles than the prosthetic hand, Version 1. This is because the increase in the grasping force increased the number of articles that the prosthetic hand, Version 2, could stably grasp when compared to prosthetic hand, Version 1.

4. Conclusions

This research demonstrated a powered prosthetic hand for children using the pneumatic artificial muscle for the purpose of assisting the daily life of a child who has a congenital or acquired unilateral arm. We devised an actuator unit to obtain the grasping force required for the drive source of the prosthetic hand for a child, and thus produced the prosthetic hand, Version 1. However, the prosthetic hand, Version 1, could not stably grasp an object weighing more than 500 g. Therefore, a further increase was required in the grasping force of the prosthetic hand designed for children.

Subsequently, we developed a prototype of the prosthetic hand, Version 2, in which the grasping force was reinforced. By using the 3D scan data of the mold that was used when manufacturing the glove as the design data for each component of the prosthetic hand, the joint position was matched with that of the glove. This enabled a stable grasping of objects weighing 500 g or more.

The basic characteristic evaluation of the prosthetic hand verified the performance of the prosthetic hand in terms of the weight, grasping force, and opening and closing time of the fingers. We measured the prosthetic hands, including the cosmetic glove, actuator unit arranged on each finger, and piping tube. The weights of the prosthetic hands, Versions 1 and 2, were 267 and 226 g, respectively. The grasping force test clarified that the average generation force of grasping by the gripping force in the prosthetic hand, Version 2, was 4.03 N, and the average generation force of precise grasping was 1.17 N. These generation forces were approximately 4.1 times greater while grasping by the gripping force and approximately 1.5 times greater in precise grasping than the forces measured in the prosthetic hand, Version 1. We confirmed that the opening and closing times of the fingers were the fastest in the prosthetic hand, Version 2, with the closing and opening times of the fingers measured to be 0.4 and 0.5 s, respectively. This indicates that the prosthetic hands can be operated more smoothly than the commercially available powered prosthetic hand and the prosthetic hand for children that uses the shape memory alloy.

The grasping ability of both prosthetic hands was evaluated using the user evaluation test. The SHAP test results indicated that objects of various shapes could be grasped and moved. In addition, the performance of the prosthetic hand, Version 2, was superior to that of the prosthetic hand, Version 1, in 75% of the overall tasks. Furthermore, a grasping experiment using a plastic bottle indicated that it was possible to grasp and lift a plastic bottle even in a state where dew condensation was generated on the surface of the plastic bottle. These experimental results suggest that the proposed prosthetic hand can be adapted in daily life.

For this experiment, we used a desktop-type compressor as the air pressure source. However, we consider that the use of a CO_2 gas cylinder can achieve wearable prosthesis in the future.

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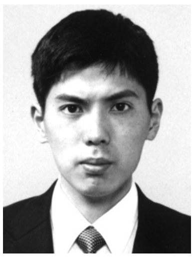

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