https://doi.org/10.20965/jrm.2022.p0454

Paper:

Development of Self-Powered 5-Finger Pneumatically Driven Hand Prosthesis Using Supination of Forearm

Kotaro Nishikawa*, **Kentaro Hirata****, **and Masahiro Takaiwa*****

*Department of Integrated Science and Technology, National Institute of Technology, Tsuyama College
624-1 Numa, Tsuyama, Okayama 708-8509, Japan
E-mail: nisikawa@tsuyama-ct.ac.jp
**Graduate School of Natural Science and Technology, Okayama University
3-1-1 Tsushima-naka, Kita-ku, Okayama 700-8530, Japan
***Graduate School of Technology, Industrial and Social Sciences, Tokushima University
2-1 Minamijyousanjima-cho, Tokushima 770-8506, Japan
[Received October 1, 2021; accepted February 9, 2022]

Recently, myoelectric hand prostheses produced by the combination of 3D-CAD and printer have gained attention. 3D printing of hand prosthesis has resulted in cost reduction. However, when an electric actuator with reduction gears is used as the driving source of the hand prosthesis, the joint rigidity becomes high; therefore, compliance control is required to grasp soft target objects. In this study, we propose a pneumatically driven hand prosthesis using a flexible bellows actuator. The hand prosthesis is lightweight and inexpensive because it is self-powered and generates compressed air through the supination motion of the user's forearm instead of an external compressor, which is essential for conventional pneumatic systems. Stable flexible grasping of the target object was achieved by driving a five-finger hand using this system.

Keywords: pneumatic, hand prosthesis, flexible grasp, back-drivability, self-powered

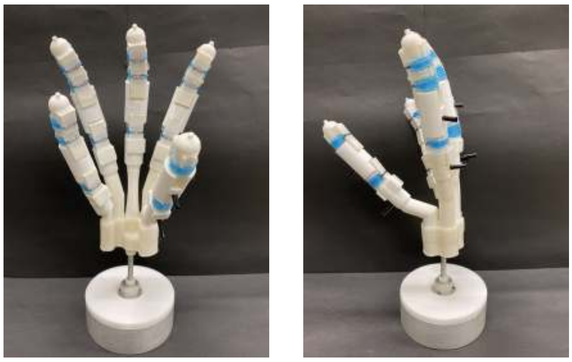
1. Introduction

Recent technological innovations in rapid prototyping, such as 3D-CAD and 3D printers, have been remarkable. This technology is actively used in the development of prototypes in the manufacturing field, which contributes to a reduction in lead time and production cost. In the medical field, the manufacture of mouthpieces for orthodontics and hearing aids [1] is expected. In the prosthesis field, a drastic reduction in the time required from measurements for casting to manufacturing is expected [2, 3]. This study focused on active hand prostheses, which have been made easy to produce owing to the spread of 3D printers. It has been reported that students in an occupational therapy department use free data to produce myoelectric hand prostheses that are lacking in clinical sites [4]. In the background of this, there is a fact that the myoelectric hand prostheses have hardly spread in the society because they are heavy in weight and expensive in cost while they have a high grasping function and decorativeness [5, 6]. The market of hand prostheses is small compared to general industrial products, and they are mostly custom-made, which are produced in accordance with the stump and forearm length of the user. Therefore, its cost is inevitably high. To reduce it by utilizing the features of rapid prototyping, myoelectric hand prostheses and hands using 3D printers have been actively developed [7–17]. Their driving sources are generally classified into electricity [7–12, 14], hydraulic, water [13], and pneumatic [14–17]. When an electric actuator with a reduction gear or hydraulic actuator is used as the driving source, a large grasping force can be expected. In contrast, the joint rigidity of the hand is extremely high that there is no back-drivability. Therefore, it is impossible to passively respond to external and contact forces from the target object. Thus, it is difficult to perform flexible motion and grasping. This suggests that achieving flexible grasping requires compliance control using a force sensor. In addition, the pneumatic actuator uses air compressed by compressor as the medium. The actuator itself is lightweight and soft and capable of reducing joint rigidity; thus, it enables passive flexible grasping without compliance control. In both electric and fluid driving, an external power source, such as a battery or compressor tank, is necessary, which increases the weight and cost. Focusing on this point, the authors developed a self-powered pneumatically driven hand prosthesis in a previous research [18]. This hand prosthesis generates compressed air through the supination motion of the user's forearm and achieves direct drive of the hand. There has been research on an self-powerd hand prosthesis [19] as a proposal for the self-powered equipment of a hydraulic system, being complicated and large in weight. This is a common problem that arises also in the case of constructing the self-powered equipment by electric and hydraulic systems, which becomes a defect in weight and cost of generator and pump unit. As a drive source of the active hand prosthesis, pneumatic driving is more desirable than electric or hydraulic because it is self-powered and results in flexible grasping. In fields other than active hand prostheses, there is intensive research on lightweight and low-cost self-powered systems, such as pneumatic walking support shoes by Takaiwa et al. [20, 21], a spring-type walking assistance device by Sano [22], and workwear using rubber from Daiya Industry Co., Ltd. [23]. Our previously developed self-powered pneumatically driven hand prosthesis [18] had 2 fingers. However, most of the hands in previous studies [7–17] have 5 fingers. A multi-finger configuration is essential for wrapping an object, including a soft target, making each finger fit to the shape of the target passively and achieving a flexible grasp in a dexterous manner.

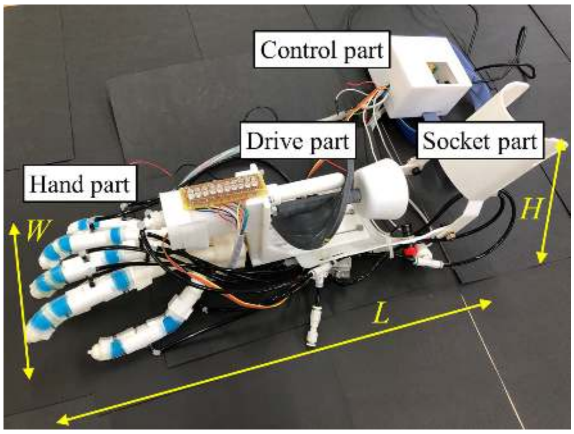
Therefore, this research proposes a 5-finger pneumatically driven hand prosthesis with pressure control using a microcomputer by extending the previously reported 2-finger self-powered pneumatically driven hand prostheses [18]. For the 5-finger hand, the one developed in [24] by the authors is used. We drive it without an external compressor aiming at the flexible grasp as wrapping the target object, which has been difficult with the 2-finger hand [18].

2. Structure and Drive Principle of 5-Finger Pneumatically Driven Hand Prosthesis

In contrast to the 2-finger case, the 5-finger hand requires more air to operate. It is beyond the amount generated by a single pumping. Therefore, in this study, the required air quantity was supplied through multiple pumping, using a microcomputer to control the pressure.[1] Controlling the pressure has several advantages. First, setting a reference pressure can limit the maximum grasping force and prevent damaging to soft target objects. Second, the grasping force can be finely adjusted. In our system, the pressurization is up to the human while the depressurization is done by the automatic control. Therefore, there is a state in which the pressure is maintained equal to or less than the reference pressure. Normally, when a check valve is used as in our case, it is impossible to return from a state of high pressure caused by excessive pumping. However, this control system reduces the bellows pressure via valve control slowly enough not to distrub grasping. The user can finely adjust the grasping force (pressure) by increasing the number of pumping and the holder angle while looking at the target object. Third, opening the valve makes it possible to release the target object instantaneously. Note that the check valve introduced this time to realize multiple fingers configuration does not allow the depressurization via a reverse operation of the pump. **Fig. 1** shows the external appearance of the self-powered 5-finger pneumatically driven hand prosthesis. The system consists of various parts: a hand, socket, drive, and control part. The hand was intended for flexible grasping similar to the human hand, and it was designed and produced based on statistical data (dimension data of hands of the Japanese) of the National Institute of Advanced Industrial Science and Technology [24]. Specifically, the finger lengths were chosen as follows: the thumb 65.0 mm, the index finger 80.0 mm, the middle finger 90.7 mm, the ring finger 86.3 mm, and the little finger 72.1 mm. This enables grasping like a human. Fourteen bellows actuators, 15.0 mm in diameter and made of polyethylene, were installed into each finger joint. The socket was attached to the user's upper arm to fix the hand prosthesis. This hand prosthesis adopts a socket used in [18]. The supination/pronation of the hand was made possible by the adduction/abduction of the shoulder of the user; thus, the target object can be grasped from above or from the side. The drive part generates compressed air. The control part consists of a microcomputer and battery for pressure control.



(a) Front view and side view (hand part) [24]

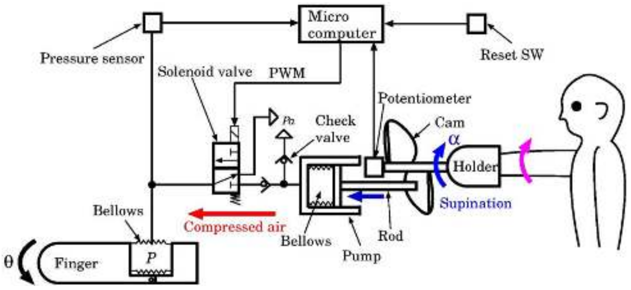


(b) Overview

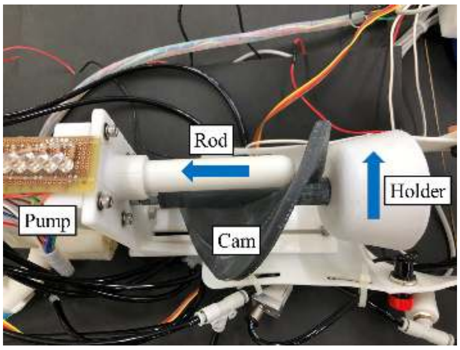
Fig. 1. 5-finger pneumatic hand.

Figure 2 shows the operating principle of the drive part. The hand prosthesis converts the supination motion of the stump inserted in the holder of the user's forearm into a linear motion by the cylindrical rib cam and compresses the built-in small pump, thereby making the drive work without external equipment such as a compressor as in [18]. The pneumatic circuit diagram is shown in **Fig. 2(a)**. Although this circuit diagram only shows one joint, five fingers are connected to one another through tubes, and all the fingers bend simultaneously in an one

1. 2-finger hand in our previous research is a direct drive system and does not use pressure feedback control.



(a) Pneumatic circuit



(b) Detail view

Fig. 2. Drive principle of 5-finger pneumatic hand.

degree of freedom manner. The 2-finger pneumatically driven hand prosthesis could grasp a rubber ball and a paper cup, but could hardly grasp target objects that require further dexterity. The use of multiple fingers is expected to solve this problem. However, the necessary pump capacity increases to introduce a direct drive without external sources. The pressure and volume required to drive the 5-finger hand were experimentally found to be approximately 80 kPa and 100 cm^3, respectively [24]. Yet, the total amount of the air required for the operation might be less than that of the hand in a previous research [15], which used an artificial muscle for the entire finger. Due to the space limitation, the pump with 100 cm^3 capacity can not be used. Thus, a check valve (CVLU4-4 manufactured by Nihon Pisco Co., Ltd.) was adopted for the pneumatic circuit to achieve the desired pressure and volume by multiple pumpings. This reduced the pump capacity and achieved the 5-finger drive without an external compressor. The stroke and the length of the cylindrical rib cam of the pump in our previous model are extended to be stored within an practically allowable space.

The control component is described here. This hand prosthesis is equipped with a pressure sensor (PSE560-01 manufactured by SMC Corporation), which monitored the bellows pressure P, and a potentiometer (RDC50A003 manufactured by Alps Alpine Co., Ltd.), which measured the rotation angle α of the holder. For the controller, a small MBED microcomputer (LPC-1768, manufactured by NXP Semiconductors) was used to drive an inexpensive direct-operated solenoid valve (G010E1, manufactured by Koganei Corporation). A digital servo pressure control system was constructed and mounted on the hand

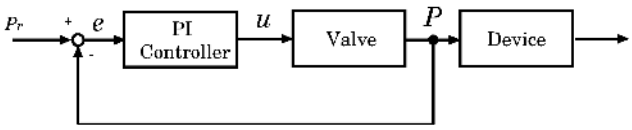
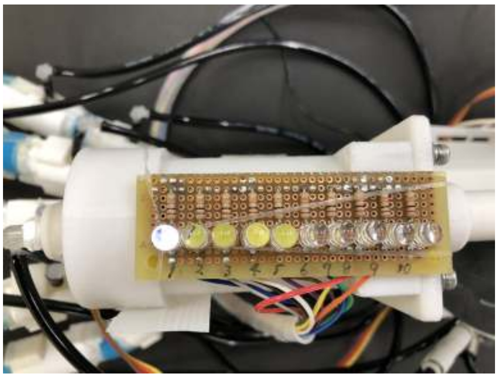


Fig. 3. Block diagram [24].

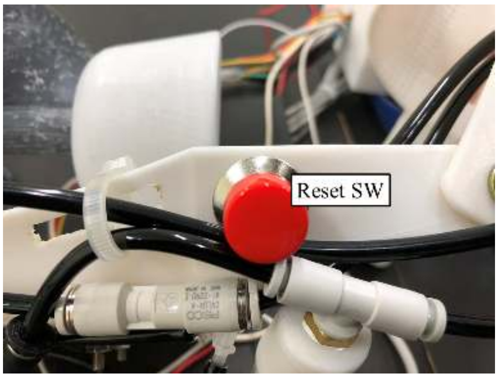
prosthesis body. The control law is a PI control. An MBED microcomputer was used to adjust the flow rate of the compressed air going into the bellows by sending a pulse-width modulation (PWM) control signal to the solenoid valve based on a control signal u generated from the deviation e between the reference pressure P_r and the measured pressure P. The maximum reference pressure (withstand pressure) was set to 100 kPa by strengthening the bellows adhesive part of the 5-finger hand. The PI control law is given by Eq. (1), where $U(s)$ is the Laplace transform of the control input, K_p and K_i are the proportional and integral gains, respectively, and $E(s)$ is the Laplace transform of the deviation. The gains of the controller were $K_p = 0.30$%/kPa and $K_i = 0.61$%/kPa·s. A block diagram is shown in **Fig. 3**.

$$U(s) = \left(K_p + \frac{K_i}{s}\right) E(s) \quad \text{. . . . . (1)}$$

The fine adjustment of the grasping force uses the pressure drop caused by the micro leakage of air under a PWM control. Therefore, although it was not possible to keep the pressure strictly constant, one can realize an intermediate pressure transiently by balancing the leakage and pumping. The reference pressure P_r is selected from 10 values (20, 25, 30, 40, 50, 60, 70, 80, 90, and 100 kPa) using a potentiometer, which detects the rotation angle of the holder. Suppose that the current pressure reference is 20 kPa. If the angle of the potentiometer exceeds 2.1 rad, then the reference is risen up to the next level, 25 kPa. To prevent an excessive rise, the rise amount is not proportional to the rotation angle. Another full rotation for 2.1 rad is needed to double the increase of the reference. Thus, the user can simultaneously set the pumping and reference pressures by adjusting the rotation angle. The appropriate setting of the reference pressure is performed by the user while looking at the target object to be grasped and the finger of the hand. For example, if the target object cannot be lifted in spite of multiple pumping, then the grasping force may be insfficient due to the low pressure reference. The reference should be raised to the next level. This is easy since the reference does not change unless the holder angle exceeds a large amount close to the physical rotation limit. Even when the reference becomes too high, the grasp force is adjusted by the depressurization effect of the PWM control. The reset switch mentioned below only triggers a complete release of the air. A fine adjustment is impossible by this switch. Because the contact force acting on the finger varies depending on the rigidity and shape of the target object, a high grasping performance is necessary for the hand. Thus, a finer resolution of the reference level over the current 10 will be



(a) Indicator



(b) Reset switch

Fig. 4. Reference pressure indicator and reset switch.

needed. (for example, two or three times). While it enables better grasping from low to high pressure, the user interface deteriorates. Therefore, this research is taking a tradeoff between the flexible grasping and the user interface by utilizing the leakage effect being a byproduct of PWM control. The user can visually recognize the present reference pressure through the LED indicator installed in the hand to enhance usability. **Fig. 4(a)** shows the external appearance of the indicator installed at the top of the pump. In this figure, one LED is lit, indicating that the reference pressure is 20 kPa. When the reference pressure is nonzero, the five fingers are bent. To extend the five fingers, the user presses the reset switch installed inside the socket, as shown in **Fig. 4(b)**. This causes the solenoid value opening, the release of the compressed air in the circuit into the atmosphere and finally, the extension of the fingers. A box in the control part stores a board mounting an MBED microcomputer and battery. The box is attached to the waist belt of the user to distribute the weight and reduce the fatigue of the forearm.

The specifications of the hand prosthesis are listed in **Table 1**. A smooth surface is required for a cylindrical rib cam that slides with a piston rod. Therefore, it is made of a Tough 2000 resin using a stereolithography 3D printer (Form 3l manufactured by Formlabs Inc.). The other components were shaped and produced using polylactic acid (PLA) resin and a fused-modeling 3D printer (MF-1000 manufactured by Mutoh Industries Ltd.). The total weight was 650 g.

Table 1. Specifications of 5-finger pneumatic hand.

Weight	650 g (without control part)
Power source	Self-powered system
Control	Pressure control using micro computer
Hand	5 fingers, 1 degree of freedom
Maximum supply pressure	100 kPa
Maximum angle of joint	Approx. 1 rad
Size	$H = 185.0$ mm, $W = 132.0$ mm, $L = 450.5$ mm

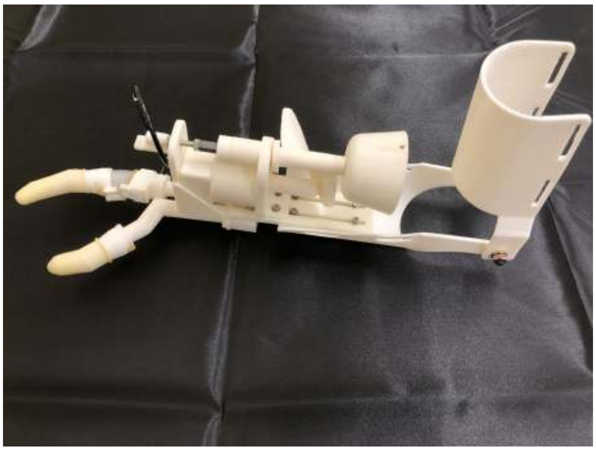


Fig. 5. 2-finger pneumatic hand.

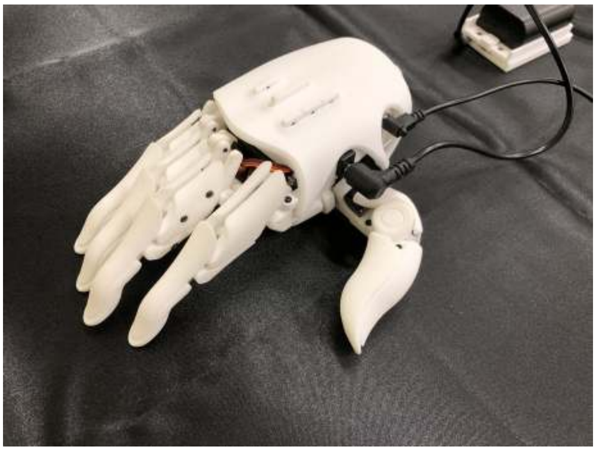


Fig. 6. 5-finger electric hand.

3. Basic Performance of the Hand Prosthesis

This section presents the quantitative evaluation of the usefulness of the proposed hand prosthesis. The comparison is made against the self-powered 2-finger pneumatic [18] and the 5-finger electric [a]. Both hand prostheses are shown in **Figs. 5** and **6**. This 5-finger hand was selected because the price is between JPY 100,000 and

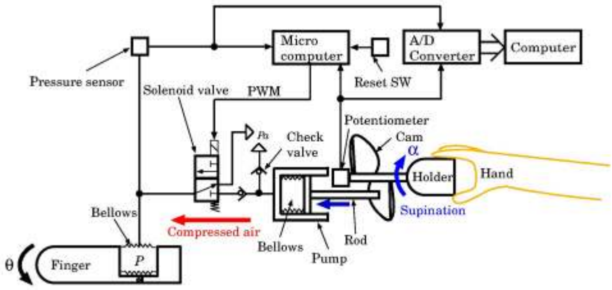


Fig. 7. Experiment system.

200,000, which is cheaper than the general electric hand prosthesis and easy to purchase. Using these hands, a grasping experiment of soft target was conducted to compare the effects of the multiple fingers configuration, the pneumatic drive, and the pressure control. Specifically, the effects of the multiple fingers were confirmed by comparing the 2- and 5-finger cases. The effects of pneumatic drive and pressure control were verified by comparing pneumatic and electric cases. A heavy-target object grasping experiment was also conducted for reference. The test subjects were three healthy adult men (A, B, and C). The task is grasp the object, lift up about 50 mm and move 400 mm left from the initial position. Three trials were conducted. Instead of inserting the stump into the holder, the test subject imitated the use of the hand prosthesis by grasping and rotating the holder with his right hand. **Fig. 7** shows the experimental apparatus. The rotation angle α of the holder was measured using a potentiometer, and the bellows pressure P was measured using a pressure sensor. The sensor output during the experiment was recorded using an external PC running on real-time Linux. The sampling time was 5.0 ms.

3.1. Soft Target Object Grasping Experiment

The target object was a corn chocolate placed in a cup (cup: colorful bento container No. 9 manufactured by Japanese Consumers' Co-operative Union; content: chocolate coated cone snack, *Ryomi 100 Sen* (100 Best Tastes) manufactured by Yamazaki Baking Co., Ltd., total weight: 48.5 g). The corn chocolate is slippy because the surface is irregular in shape and coated with chocolate. Pieces of corn chocolate were placed in a flexible paper cup and having a point contact against each other in an unstable manner. Thus, there was a concern that even a small change in external force or in acceleration during grasping and moving could cause fall of the corn chocolate or the cup. The test subject grasps and moves the target object by the prosthesis in his hand while confirming its state. The results of the grasping experiment are as follows.

The results for the 2-finger hand prosthesis are shown in **Fig. 8**. **Fig. 8(a)** shows sequence of photographs at timing (A) to (C) shown in **Fig. 8(b)** of Subject A. **Fig. 8(b)** shows the time responses of the holder rotation angle and the bellows pressure (grasping force). This indicates that, although the supination angle of the holder was adjusted the grasping is attempted, the corn chocolate spilled over from the 2 fingers, and the grasping failed. Subjects B and C, as shown in **Fig. 8(c)**, also failed to grasp.

The results for the 5-finger are shown in **Fig. 9**. The test subjects attempted to grasp the corn chocolate by carefully controlling the electric hand prosthesis. Because it is a 5-finger, it wrapped and grasped the corn chocolate. However, due to a lack of back-drivability, the electric hand prosthesis could not adapt to the change in the surface shape of the paper cup, and failed.

The results for the 5-finger pneumatically driven case are shown in **Fig. 10**. In **Fig. 10(a)**, one can observe that the surface shape of the cup is changing as the chocolates inside move during the task. However, the influence was passively absorbed by the flexibility and back-drivability of the pneumatic drive; thus, stable grasping was successfully performed. As shown in **Fig. 10(b)**, the reference pressure was adjusted to 30 kPa by the test subjects. It took approximately 10 s from [B] to [C] because the test subjects were pumping while checking the state of the corn chocolate. It can be observed that the finger joint at that time had low rigidity owing to the appropriate setting of the internal pressure. In the abovementioned grasping experiment, the test subjects succeeded in grasping the corn chocolate, which required passive grasping, by appropriately setting the finger joint rigidity of the 5-finger hand.

3.2. Heavy Target Object Grasping Experiment

In the previous subsection, we observed that the pressure increases in proportion to the number of the pumping. For reference, the result of the grasping experiment for a heavy target object is discussed here. The grasping target was a 440 mL PET bottle filled with the content. This is heavier than the PET bottle grasped in previous research [18, 24].

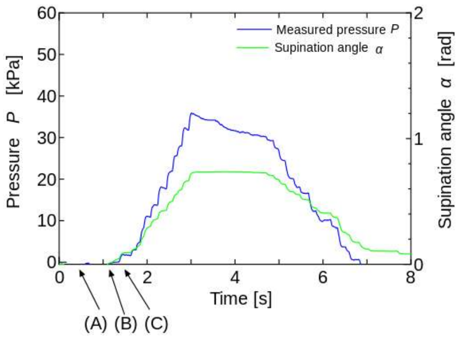
The results for the 2-finger case are shown in **Fig. 11**. The test subjects manipulated the 2-finger hand to grasp the PET bottle. However, they failed because of small grasping force due to shortage of pump capacity; thus, the PET bottle slid and dropped from the finger.

Figure 12 shows the results of the 5-finger electric case. Using this hand, all the test subjects successfully grasped the PET bottle, owing to the grasping force caused by the large torque of the electric actuator.

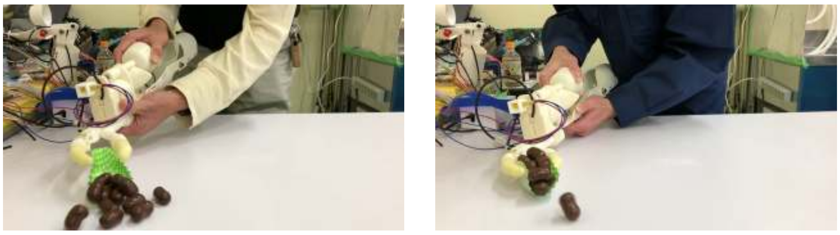
Figure 13 shows a scene of the 5-finger pneumatically driven hand. **Fig. 13(a)** shows the fingers wrapping the PET bottle along the wavy side surface. In spite of the heavy weight, all the test subjects successfully grasped it with a large grasping force. **Fig. 13(b)** shows that the reference pressure was adjusted to 70 kPa by Subject A to increase the bellows pressure. Correspondingly, the finger joints became rigid, thus grasping was successfully performed. However, approximately 15 pumping over a period of 22 s were required in the process. In addition to the rattling of the piston rod and cylindrical rib cam, this

[A] Approach [B] Grasp [C] Fall

(a) Photograph of time transition of Subject A



(b) Graph of supination angle and pressure of Subject A



(c) Photograph of the time transition of Subjects B and C

Fig. 8. Grasping of a chocolate cone in a cup using 2-finger pneumatic hand.

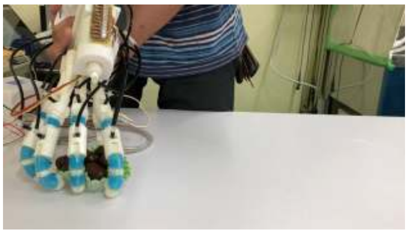
[A] Approach [B] Grasp [C] Fall

(a) Photograph of time transition of Subject A

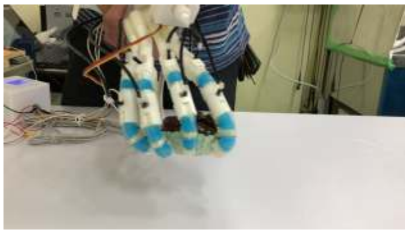
(b) Photograph of the time transition of Subjects B and C

Fig. 9. Grasping of a chocolate cone in a cup using 5-finger electric hand.

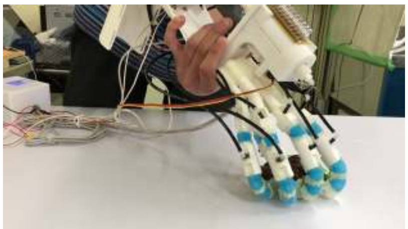
[A] Approach



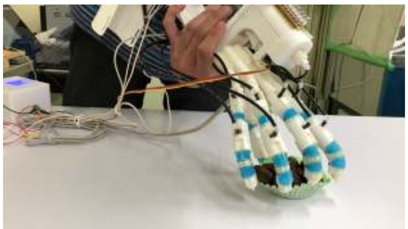
[B] Grasp



[C] Up · Move

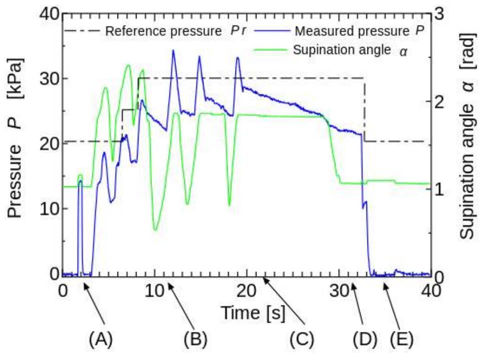


[D] Down

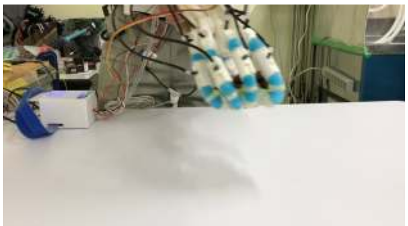


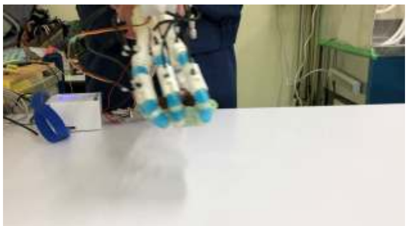
[E] Release

(a) Photograph of time transition of Subject A



(b) Graph of supination angle and pressure of Subject A





(c) Photograph of the time transition of Subjects B and C

Fig. 10. Grasping of a chocolate cone in a cup using 5-finger pneumatic hand.

is partly brought by the pressure loss when the pressure control is awakend at the timing of the reference change. The need for continuous pumping is not realistic in terms of the operability of the hand prosthesis.

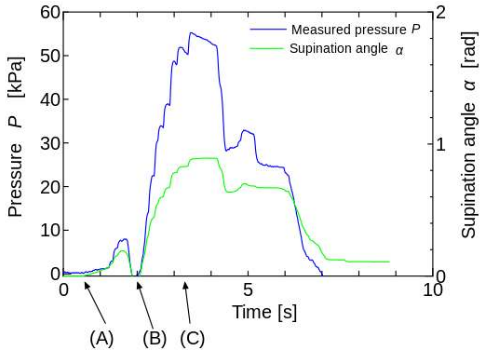
3.3. Discussions on Grasping Experiment

Table 2 presents the results of the soft and heavy target object grasping experiments. Comparing 2 and 5 fingers pneumatic drive cases, the success rate of grasping both target objects in the former was 0%, whereas that in the latter was 100%. This is simply because the number of the fingers are different, whether a wrapping around the target object is possible or not. The 2-finger hand only allow a pinch motion and it inevitably increases the contact force per finger. The limit on the friction might be the reason of the failure. This suggests that multiple fingers contribute to an improvement in the grasping performance of the hand.

The electric and pneumatic 5 fingers cases were also compared. It was shown that the difference of the driving methods strongly influences the experimental result. The electric hand brought a large grasping force to the five fingers through the servomotor with a reduction gear, and all the test subjects stably grasped the PET bottle. However, a lack of back-drivability prevents the fingers to fit the side surface of the PET bottle. This is critical in the

[A] Approach [B] Grasp [C] Fall

(a) Photograph of time transition of Subject A



(b) Graph of supination angle and pressure of Subject A

(c) Photograph of the time transition of Subjects B and C

Fig. 11. Grasping of a PET bottle using 2-finger pneumatic hand.

corn chocolate experiment. The fingers could not flexibly cope with the change in shape of the corn chocolate (paper cup) through the external force, and failed. In contrast, the pneumatic drive case stably grasped the side surface of the PET bottle owing to the low rigidity caused by the back-drivability. It also achieved a flexible grasping of the corn chocolate. This suggests that a pneumatic drive is useful for flexible grasping.

Finally, the control methods are compared. The electric hand controls the uplift quantity of the muscle using the sensor. It allows the user to carry out intuitive manipulation, and provides an excellent interface easy to operate via practice. However, it is difficult to dexterously move each finger in accordance with the target object. On the contrary, the pneumatic hand hardly gives psychological anxiety of "possibly crushing the target object" because, even if continuous pumping is required to grasp the PET bottle, the maximum grasping force is restricted by pressure control, as well as the passive grasping case of the corn chocolate. Decompression actuation of the automatic control system allowed to finely adjust the grasping force just enough. Therefore, all the test subjects succeeded in grasping the corn chocolate.

The abovementioned results indicate that the proposed 5-finger hand prosthesis could grasp from a soft target object to a heavy one owing to the synergistic effect of the multiple fingers, pneumatic drive, and pressure control.

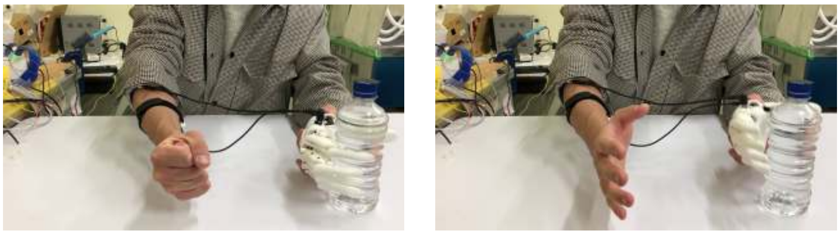
4. Conclusions

In this study, we proposed a self-powered 5-finger pneumatically driven hand prosthesis without an external compressor, and evaluated its performance. As a result, we found the following:

A digital servo system that uses the supination motion of the user's forearm as a pressure source was successfully implemented. Although the number of pumping increased, accompanied by the multiple fingers, the pressure control enabled more stable grasping.

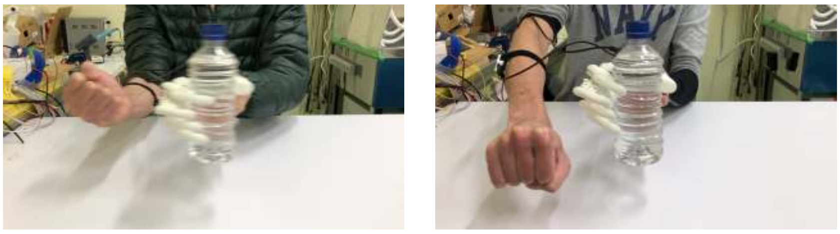
In the experiment for the soft target, the hand prosthesis developed in this study succeeded in grasping the corn chocolate placed in a paper cup, which was considered relatively difficult to handle.

[A] Approach [B] Grasp [C] Up · Move



[D] Down [E] Release

(a) Photograph of time transition of Subject A



(b) Photograph of the time transition of Subjects B and C

Fig. 12. Grasping of a PET bottle using 5-finger electric hand.

In future, we will examine a system that accumulates pressure in a tank to grasp heavy objects. For example, a system is conceivable in which air is accumulated in a small and lightweight tank installed at the waist of the user by using the foot pump [20, 21] installed at the sole of the shoe. When a large grasping force is required, the number of pumping can be reduced and the operability of the hand prosthesis can be enhanced if the hand is driven by both pumping by the user and compressed air in the tank. However, pumping these foot pumps can be done only by walking. In other words, it cannot be used as a substitute for the supination pump for grasping when we are not walking. The role of the foot pump is restricted to an assistive one to the supination. Unlike the human hand, the proposed hand prosthesis has no dexterity. To further improve the grasping performance for soft target objects, the reproduction of dexterity, that is, the multiple degrees of freedom of the hand (corresponding to the grasping pattern such as holding and pinching) will also be examined.

Acknowledgments

We would like to express our gratitude to Mr. Daisuke Kawakami, Department of Advanced Engineering Course, National Institute of Technology, Tsuyama College, and Kaiki Nishiyama and Ren Hamada, Department of Integrated Science and Technology, National Institute of Technology, Tsuyama College, for the efforts they provided for our research. Part of this research was supported by the Grant-in-Aid for Scientific Research 19K14954 and by the National Institute of Technology College Faculty Research Ability Enhancement Program (Junior) of the 2021 fiscal year.

References:

[1] H. Kobayashi, "3D Printing Technology and Application: Now and Future," J. of Printing Science and Technology, Vol.50, No.5, pp. 413-421, 2013 (in Japanese).

[2] M. Okuno, "3D Digital Technology Initiatives in the Field of Prothesis and Orthosis in Japan," J. of the Japanese Society of Prosthetics and Orthotics, Vol.36, No.3, pp. 198-199, 2020 (in Japanese).

[3] Y. Kodama, "3D Digital Technology Initiatives in the Field of Prothesis and Orthosis in France," J. of the Japanese Society of Prosthetics and Orthotics, Vol.36, No.3, pp. 194-197, 2020 (in Japanese).

[4] Y. Oki, T. Arikawa, and T. Marumoto, "Report of a Project to Produce a Myoelectric Prosthetic Hand using 3D Printer," Bulletin of Faculty of Fukuoka Medical Technology Teikyo University, No.16, pp. 67-71, 2021 (in Japanese).

[5] O. Kashimoto, "Issues through Financial Support for the Myoelectric Upper Limb Prosthesis under the Services and Supports for Persons with Disabilities Act," J. of Occupational Medicine and Traumatology, Vol.61, No.5, pp. 305-308, 2013 (in Japanese).

[6] Y. Tanaka, "Current Status and Future Prospects of Myoelectric Prostheses," J. of the Japanese Society of Prosthetics and Orthotics, Vol.34, No.2, pp. 110-114, 2018 (in Japanese).

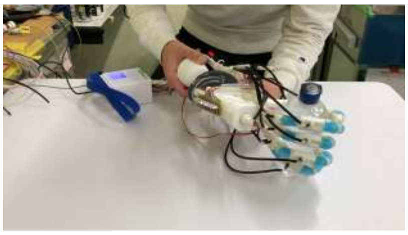
[7] T. Tsuji, A. Furui, and G. Nakamura, "Electromyographic Interface Technology and Robotic Arm Prostheses," J. of the Japan Society for Precision Engineering, Vol.83, No.11, pp. 1110-1113, 2017 (in Japanese).

[8] S. Ahmed, A. Almusawi, B. Yilmaz, and N. Dogru, "Design and Multichannel Electromyography System-based Neural Network Control of a Low-cost Myoelectric Prosthesis Hand," J. of Mechanical Sciences, Vol.12, No.1, pp. 69-83, 2021.

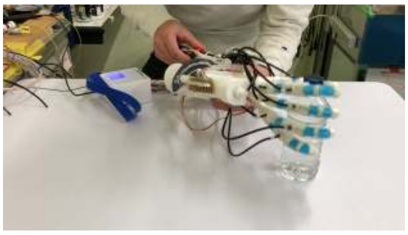
[A] Approach

[B] Grasp

[C] Up · Move

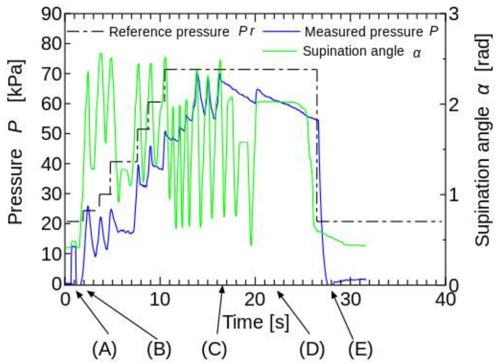


[D] Down

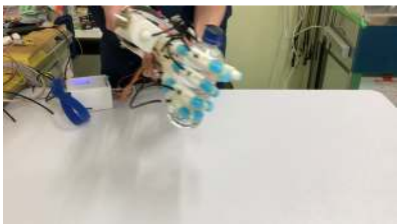


[E] Release

(a) Photograph of time transition of Subject A



(b) Graph of supination angle and pressure of Subject A



(c) Photograph of the time transition of Subjects B and C

Fig. 13. Grasping of a PET bottle using 5-finger pneumatic hand.

Table 2. Results of grasping experiment.

Subject	2finger self-powered pneumatic hand		5finger electric hand		5finger self-powered pneumatic hand	
	Chocolate cone	PET bottle	Chocolate cone	PET bottle	Chocolate cone	PET bottle
A	× / × / ×	× / × / ×	× / × / ×	◯ / ◯ / ◯	◯ / ◯ / ◯	◯ / ◯ / ◯
B	× / × / ×	× / × / ×	× / × / ×	◯ / ◯ / ◯	◯ / ◯ / ◯	◯ / ◯ / ◯
C	× / × / ×	× / × / ×	× / × / ×	◯ / ◯ / ◯	◯ / ◯ / ◯	◯ / ◯ / ◯

[9] M. Yoshikawa, "Three-fingered Electric Prosthetic Hand Produced with a 3D Printer," J. of the Japanese Society of Prosthetics and Orthotics, Vol.32, No.3, pp. 154-159, 2016 (in Japanese).
[10] M. Yoshikawa and N. Kawashima, "Commercialization and Promotion of Electric Prosthetic Hand "Finch"," J. of the Robotics Society of Japan, Vol.38, No.2, pp. 131-134, 2020 (in Japanese).
[11] M. Yoshikawa, "Upper Limb Prostheses Developed with Digital Fabrication Tools," J. of the Japanese Society of Prosthetics and Orthotics, Vol.34, No.2, pp. 115-118, 2018 (in Japanese).
[12] A. Mohammadi, J. Lavranos, H. Zhou, R. Mutlu, G. Alici, Y. Tan, P. Choong, and D. Oetomo, "A Practical 3D-printed Soft Robotic Prosthetic Hand with Multi-articulating Capabilities," J. of Plos One, Vol.15, No.5, pp. 1-23, 2020.
[13] I. Nicolas, C. Pylatiuk, S. Schulz, A. Kargov, R. Oberle, and T. Werner, "The Fluidhand III: A Multifunctional Prosthetic Hand," J. of Prosthetics and Orthotics, Vol.21, No.2, pp. 91-96, 2009.
[14] D. Riet, R. Stopforth, G. Bright, and O. Diegel, "The Low Cost Design of a 3D printed Multi-fingered Myoelectric Prosthetic Hand," J. of Mechatronics: Principles, Technologies and Applications, Ch.4, pp. 85-117, 2015.
[15] H. Yamashita, T. Doi, Y. Yamada, T. Nomura, and T. Noritsugu, "Development of a Prosthetic Terminal Device using Pneumatic Artificial Muscle," Proc. of the 2019 JSME Conf. on Robotics and Mechatronics, 2A1B05, 2019 (in Japanese).
[16] S. Yamaguchi and H. Tomori, "Development of Human Like Robotic Hand using Pneumatic Artificial Rubber Muscle," Proc. of 329th Research Meeting on the Society of Instrument and Control Engineers Tohoku Chapter, pp. 1-5, 2020 (in Japanese).
[17] Z. Wang, A. Wada, Y. Mori, and S. Kawamura, "Development of Pneumatic Soft Robotic Hands using 3D Printer," J. of the Robotics Society of Japan, Vol.39, No.4, pp. 298-301, 2021 (in Japanese).
[18] K. Nishikawa, K. Hirata, and M. Takaiwa, "Development of Self-Powered Pneumatic Prosthetic Hand with Tactile Feedback," Trans. of the Japan Fluid Power System Society, Vol.49, No.2, pp. 56-63, 2018 (in Japanese).
[19] R. Fujino, "Above Knee Prosthesis for Ascending / Descending Stairs with no External Energy Source," J. of the Society of Instrument and Control Engineers, Vol.57, No.9, 663, 2018 (in Japanese).
[20] M. Takaiwa and T. Noritsugu, "Development of Energy Autonomous Type Pneumatic Walking Support Shoes," J. Robot. Mechatron., Vol.21, No.3, pp. 353-358, 2009.
[21] M. Takaiwa and S. Yamashina, "Development of Self-powered Pneumatic Walking Assistance Device Intended for Diabetics," Proc. of the 2019 JSME Conf. on Robotics and Mechatronics, 2A1-C16, 2019 (in Japanese).
[22] A. Sano, "Unpowered Walking Assistance Device by using Ingeniously a Gravitational Field," J. of the Robotics Society of Japan, Vol.38, No.2, pp. 139-142, 2020 (in Japanese).
[23] K. Okuyama, "500g workwear to assist unpowered, human-powered excavation," Nikkei Construction, Vol.745, p. 26, 2020 (in Japanese).
[24] K. Nishikawa, K. Hirata, and M. Takaiwa, "Development of Pneumatically Driven Hand Capable of Grasping Flexible Objects," J. Robot. Mechatron., Vol.32, No.5, pp. 923-930, 2020.

Supporting Online Materials:

[a] HACKberry Open Source Community. http://exiii-hackberry.com/ [Accessed December 10, 2021].

Name:
Kotaro Nishikawa

Affiliation:
Associate Professor, Department of Integrated Science and Technology, National Institute of Technology, Tsuyama College

Address:
624-1 Numa, Tsuyama, Okayama 708-8509, Japan

Brief Biographical History:
2004- Kawasaki Precision Machinery (Kawasaki Heavy Industries, Ltd.)
2008- Engineering Official, Support Center for Education and Research, National Institute of Technology, Tsuyama College
2018- Assistant Professor, Department of Integrated Science and Technology, National Institute of Technology, Tsuyama College
2019- Senior Assistant Professor, Department of Integrated Science and Technology, National Institute of Technology, Tsuyama College
2021- Associate Professor, Department of Integrated Science and Technology, National Institute of Technology, Tsuyama College

Main Works:
• "Development of Pneumatic Bellows Myoelectric Hand with Tactile Feedback," Trans. of the Institute of Electrical Engineers of Japan C, Vol.137, No.1, pp. 127-135, 2017.
• "Development of Self-Powered Pneumatic Prosthetic Hand with Tactile Feedback," Trans. of the Japan Fluid Power System Society, Vol.49, No.2, pp. 56-63, 2018.

Membership in Academic Societies:
• The Japan Society of Mechanical Engineers (JSME)
• The Japan Fluid Power System Society (JFPS)

Name:
Kentaro Hirata

Affiliation:
Professor, Graduate School of Natural Science and Technology, Okayama University

Address:
3-1-1 Tsushima-naka, Kita-ku, Okayama 700-8530, Japan

Brief Biographical History:
1996- Associate Researcher, Kyoto University
1998- Senior Assistant Professor, Osaka Prefecture University
2005- Associate Professor, Nara Institute of Science and Technology
2014- Professor, Okayama University

Main Works:
• "On Internal Stabilizing Mechanism of Passive Dynamical Walking," SICE JCMSI, Vol.4, No.1, pp. 29-36, 2011.
• "Numerical Methods for Spectrum Computation of Monodromy Operators via Non-Causal Hold Discretization," SICE JCMSI, Vol.6, No.1, pp. 45-53, 2013.
• "Energy-Efficient Power Assist Control with Periodic Disturbance Observer and its Experimental Verification Using an Electric Bicycle," SICE JCMSI, Vol.10, No.5, pp. 410-417, 2017.

Membership in Academic Societies:
• The Institute of Electrical and Electronics Engineers (IEEE)
• The Society of Instrument and Control Engineers (SICE)
• The Institute of Systems, Control and Information Engineers (ISCIE)

Name:
Masahiro Takaiwa

Affiliation:
Professor, Graduate School of Technology, Industrial and Social Sciences, Tokushima University

Address:
2-1 Minamijyousanjima-cho, Tokushima 770-8506, Japan

Brief Biographical History:
1992- Associate Researcher, Okayama University
2000- Lecturer, Okayama University
2007- Associate Professor, Okayama University
2015- Professor, Tokushima University

Main Works:
- M. Takaiwa, T. Noritsugu, D. Sasaki, and T. Nogami, "Fingertip Force Displaying Device Using Pneumatic Negative Pressure," Int. J. Automation Technol., Vol.8, No.2, pp. 208-215, 2014.
- M. Yokota and M. Takaiwa, "Development of Non-Wearing Type Pneumatic Power Assist Device – Basic Concept and Performance Evaluation –," J. Robot. Mechatron., Vol.32, No.5, pp. 1052-1060, 2020.
- M. Yokota and M. Takaiwa, "Gait rehabilitation system using a non-wearing type pneumatic power assist device," J. Robot. Mechatron., Vol.33, No.4, pp. 927-934, 2021.

Membership in Academic Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Japan Fluid Power System Society (JFPS)
- The Robotics Society of Japan (RSJ)
- The Virtual Reality Society of Japan (VRSJ)