Design and Characterization of Low-Cost Soft Pneumatic Bending Actuator for Hand Rehabilitation

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***Abstract*— In an assistive device such as hard exoskeleton hand, there are some disadvantages, such as hard to align with the user's finger, still solid / rigid form that allows a broken part when colliding with other solid/hard objects. In this research, soft Pneumatic Bending Actuators (PBA) are developed as wearable robot based on soft robot technology for hand rehabilitation or assistive device. The proposed soft PBA uses pressurized air chamber in the silicon rubber material performing a bending motion for supporting the flexion/extension motion of the human finger when it is worn by human hand. Selected low-cost RTV (Room-Temperature-Vulcanizing) Silicone will be used to build a soft PBA. The PBA mold is designed using CAD software and printed using 3D print. The prototype of the PBA will be tested by giving air pressure and acquiring the bending angle response. Based on the test results, the bending angle on the soft PBA shows that the bending angle of unattached PBA on the human finger has higher bending angle than the PBA attached on the human finger.**

Keywords—silicone rubber, pneumatic bending actuator, soft robot

I. Introduction

Hand is one of the crucial part of the body for human to perform daily activities. However, hand injuries due to an accident on the hand are the most common. As a result of this accident is reduced motoric ability of the hand so that therapy is needed to restore motor function of the hand on a person. In addition to accidents, hand disabilities can be caused by certain diseases, one of which is a stroke.

A robotic therapy device is a necessary tool in the field of medical rehabilitation in patients suffering from hand paralysis due to minor stroke. Robotic therapy tool is expected to be a companion therapy tool from conventional therapeutic methods that aim to accelerate the recovery of patients with the principle of re-education and motor learning.

Assistive robot for medical purpose has been widely used in the daily life of patients who experience the situation of gesture dysfunction. It is expected that an assistive robot can provide an effective and efficient role in helping patients activities due to hand function disability. One of the assistive or rehabilitation robot that has been researched and produced is hard exoskeleton hand for patients with hand discomfort due to stroke diseases on the function of rehabilitation and assistive. This technology uses hard or rigid material as the main material of the robot.

In such assistive devices as hard exoskeleton hand robot, there are some disadvantages, such as a still solid / rigid form that allows a broken when colliding with other solid objects that have the same or more hardness [1]. The hard robot also has the difficulty in alignment with the human fingers. In addition, the mass of hard exoskeleton hand is still heavy to be supported by human hands in general, moreover the hand of the patient/person has paralyzed hands. That is the reason why researchers develop this research for future soft robot as an assistive or rehabilitation device. It can be a device that is friendly to the patient in terms of activity and usage functions. It is called soft robot because the material used in the manufacture of the robot has a form that is not solid, not rigid, and flexible. Based on the patient comfort consideration when using wearable robot. This is because some problems in robotic device that has been produced before that still use hard robot such as difficult to alignment and less comfortable when worn.

Soft robot is specific area of a robot that deal with the producing of robots from soft materials, similar to those found in living organisms. In contrast to the robots built from rigid materials, soft robots allow for increasing flexibility and adaptability to complete tasks, as well as security while working around humans [2].

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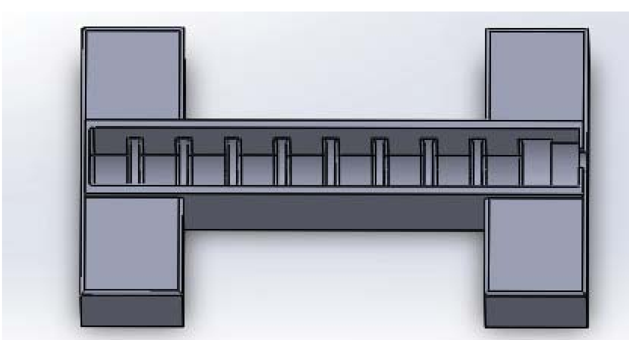
In this study, we want to develop a wearable robot based on soft robot technology for hand rehabilitation or assistive device that is Pneumatic Bending Actuator (PBA). recently, PBAs have been developed by researchers as soft robotic glove for rehabilitation device [[3]–[7]]. This PBA uses air chamber in elastomer or silicon rubber material performing bending motion for supporting the motion of the human finger when it is worn by human hand.

This research will be focused on the design and characterization of the Pneumatic Bending Actuator (PBA) for post-stroke hand rehabilitation purpose. Selected low-cost RTV (Room-Temperature-Vulcanizing) silicone will be utilized to build a PBA. The PBA mold is designed using CAD software and printed using 3D print. The prototype generated from the PBA will be tested by giving air pressure and acquiring the bending angle response. The PBA will be tested when unattached and attached to the human finger.

II. PBA Design and Manufacture

After the PBA sketch was formed, the next thing to do was to convert the shape of the sketch into 3D model design in CAD (computer aided design) software. In this process, there were several aspects that need to be considered so that the manufacturing process can produce near enough perfect or perfect. This process is focused on the functional aspects of the PBA and the ease aspects of the manufacturing process. The 3D design stage of PBA mold and glove base used SolidWorks software. SolidWorks was used to get the visual appearance of the mold design that was made whether it was in accordance with the desired design form. The 3D CAD design of the PBA mold consisted of three parts; segment, cavity, and base. 3D CAD model of the design mold of PBA can be seen in Fig. 1. The final result 3D model of CAD design of PBA molded from low-cost RTV (Room-Temperature-Vulcanizing) silicone is shown in Fig, 1.d.



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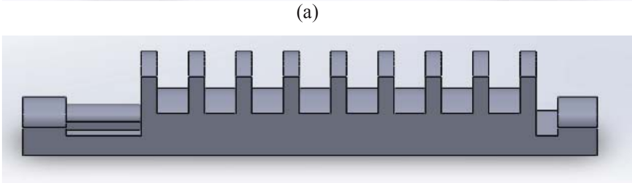


(b)

(c)

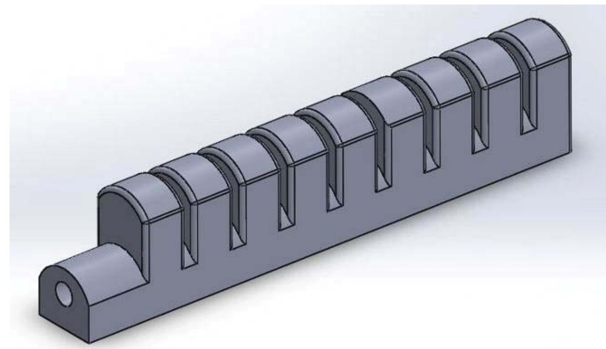


Fig. 1. 3D printing mold, (a) Segment, (b) Cavity, (c) Base, (d) Resulted PBA design

The material used to produce soft PBA was by using silicone rubber material. Based on the manufacturing temperature of silicone rubber, it consisted of two types, which require heating and does not require heating or which is often called RTV (Room-Temperature-Vulcanization). RTV itself has many different types based on the stiffness, heat resistance, and mixed type. In this study, silicone rubber was selected by using RTV type, RTV type silicone rubber was chosen to facilitate the manufacturing process, because the manufacturing process did not require additional tools such as heating and this research was conducted at low or room temperatures. There are three types of RTV silicone that have been widely used, RTV 48, RTV 52 and RTV Platinum. Silicone rubber RTV type is chosen because it is easy to get and the price is relatively cheap. The selection of three materials above is based on the several criteria, such as stiffness, casting result, and price per kilogram. Table I shows a comparative summary among the three RTV type silicone rubber materials.

Based on the RTV silicone rubber comparison as shown in Table I, the RTV platinum was selected as the main material for producing low-cost soft PBA. RTV Platinum was chosen because it has the stiffness that suits the needs, and also based on the consideration of the availability of silicone rubber material in the market. The point of RTV Platinum rigidity was highest when compared to RTV 48 which stiffness was too low, so the PBA using this material could not work as desired because it was too soft and RTV 52 stiffness is higher than RTV 48 but not rigid enough for the base material for producing the soft PBA.

TABLE I. ADVANTAGES AND DISADVANTAGES OF RTV SILICONE

Properties	RTV 48	RTV 52	RTV Platinum Catalyst
Advantages	▪ Quick drying ▪ No need much catalyst	▪ More elastic ▪ Using less catalysts	▪ Quick drying ▪ he resulted cavitation is low ▪ Low viscosity ▪ Tends to be denser when dry ▪ Easy fill in small gaps while casting
Disadvantages	▪ The result is too soft ▪ Cavitation that appear relatively numerous ▪ The viscosity value is quite high ▪ Difficult to fill small gaps while casting	▪ Long drying ▪ Cavitation that appear in moderation ▪ Tend to soft when dry	▪ If the catalyst is not suitable, it will easily get wet or easily brittle ▪ It needs a longer vacuum process ▪ More catalysts needed

The advantages of RTV Platinum when casting, RTV Platinum can enter and fill the narrow gaps so that the results of soft PBA can be formed perfectly, as well as other RTV. But the concern here was the casting result, where RTV 48 produces the final soft PBA formed that did not match the desire, such as the number of molding fibers that had been printed so that the surface of the casting becomes less attractive and the results were too soft. Furthermore, in terms of raw material prices obtained from online stores (e-commerce) in Indonesia, RTV Platinum is the most expensive.

In the PBA mold design process, this process was conducted using SolidWorks software. In this process, it showed the visualization of each mold to verify whether the design was appropriate or not. The final design of the PBA mold will be printed in 3D printers with PLA filament material. Prior to printing, 3D CAD design files have changed formatting when using 3D printers. Then the 3D printer will start printing the design to completion. After the PBA mold was finished, the print dimension was checked whether it was appropriate and the smoothness was within the tolerable limit. The finished 3D print of soft PBA mold can be seen on Fig. 2.

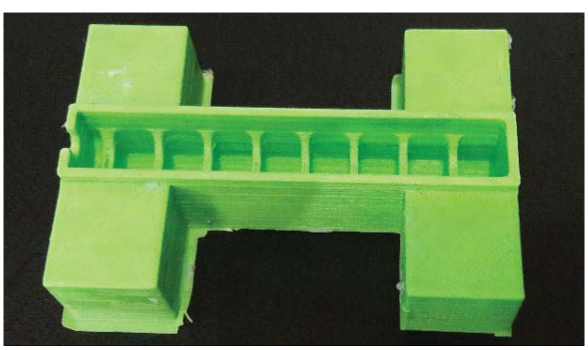


Fig. 2. Resulted mold using 3D printing technology

The catalyst mass ratio compared to RTV silicone was 1:10 of the mass of silicone rubber. The function of the catalyst is to make the silicone rubber liquid becomes hard. Measurement of catalyst dosage was performed by using digital scales. If the catalyst was used too much, it could make the rubber silicone became too hard until the air pump was not strong to soften the soft PBA. The catalyst used for the manufacture of the segment was 7 grams, and for the base was 4 grams. After mixing the silicon rubber liquid with the catalyst, the coloring of the PBA can be performed by pouring the catalyst on a measuring cup already filled with silicone rubber and poster paint. The poured catalyst shall be in accordance with the specified dosage so that the casting yield did not require an extended time for the drying process. After the catalyst, the silicone rubber liquid, and the poster paint were poured, then all the materials were stirred together. In the stirring stage, it was preferably conducted quickly and the stirrer need not be removed to avoid any cavitation in the mixture. The cavitation formed during stirring can be removed by degassing or vacuum process. This should not be allowed because microscopic cavitation can cause leaks in soft PBA and the soft PBA cannot perform its function when applied with pressurized air. The process of vacuum in this study can be seen in Fig. 3. When the vacuum process has reached the desired vacuum pressure, then the vacuum process has been completed. The next step was to pour the mixture of silicon rubber that has been vacuumed into the mold segment and base as shown in Fig. 4. Then attach the segment and base that already contains a mixture of silicone rubber so that it became one. Then the silicone rubber dried at room temperature. After the silicone rubber mixture dried, the soft PBA that has been produced can be seen as in Fig. 5.

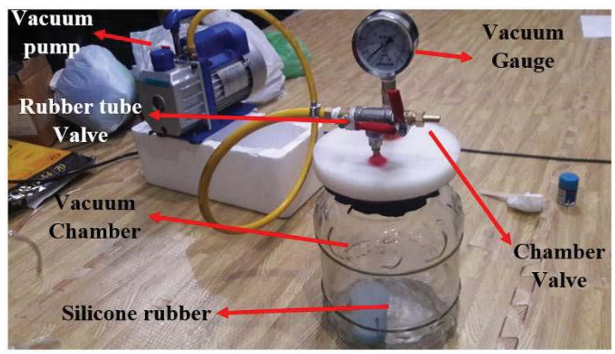
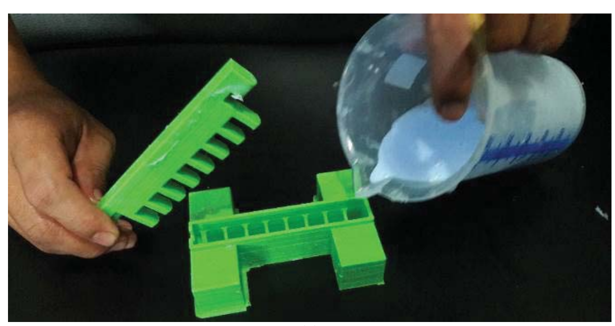
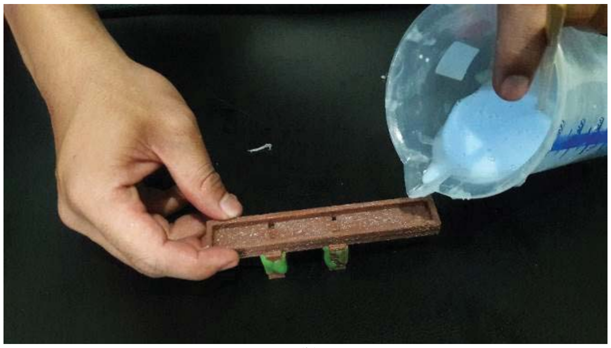


Fig. 3. Vacumm process of silicone rubber



(a)



(b)

Fig. 4. Molding process (a) Segment, (b) Base

Fig. 5. The finished PBA prototype

III. HARDWARE SYSTEM

The PBA that has been developed will be placed on a soft robotic glove and can be used by human hand as a rehabilitation tool for post-stroke patients. Therefore, mechanical and electrical components such as a microcontroller, battery, actuator, valve, hose etc. can be placed in human body part such as waist. In this study, Arduino MEGA 2560 was chosen as an embedded system for the control system of the pneumatic network from PBA. Arduino MEGA 2560 has memory and computation speed required for controlling how much the PBA will bend when it was given by air pressure input. Arduino MEGA 2560 has 54 digital input/output (DIO) where 14 DIO pins can be used for PWM output and 16 pins are used as analog input, 4 pins for UART, 16 MHz crystal oscillator, USB connection, power jack, ICSP Header, and reset button.

The solenoid valve was used to regulate, direct or control the pressurized air flow by opening, closing or partially closing the airflow. In this study, the valve used in soft PBA was a mini electric solenoid valve that requires voltage of 12 V and has three airflow directions. Fig. 6 shows a mini electric solenoid valve that was used to regulate airflow on the proposed PBA.

Pressure sensor is used to measure the pressure of a fluid and then convert the pressure value into an electrical voltage signal. In this study, the used pressure sensor was the MPX5500DP pressure sensor. This sensor can read pressure up to 500 kPa that has analog voltage output. The selected MPX5500DP pressure sensor can be shown in Fig. 7.

Fig. 6. Selected mini electric solenoid valve

Fig. 7. Selected pressure sensor MPX5500DP

The actuator used in this research was miniature water/air diaphragm pump. This actuator moved the fluid from a lower pressure to a higher pressure or a lower position to a higher position. In Fig. 8 shows the mini air pump used in the pneumatic network system of PBA. The nominal air flow rate on this pump is 5 L/minute at 12 V and consumes power at 2.5 Watts. L293D driver motor is utilized in this research for controlling the speed of the actuator/pump.

Fig. 8. Selected mini air compressor

The proposed soft PBA is driven by a pneumatic network system where silicone PBA acts as an actuator that can move curved when pressurized air and returns straight when the pressurized air is removed. This movement is like the movement of flexion and the extension of human finger. To drive the proposed PBA, the air is compressed from the mini air compressor through the hose into the hollow PBA silicone. The system is maintained so that no air leaks out when the valve is not ordered to function. Therefore, there will be an increased pressure value when the air becomes compressed in the PBA. The pressure value is read by MPX5500DP type pressure sensor. The entire pneumatic network system scheme in PBA can be seen in Fig. 9. In broader terms, all the considerations designed in the final prototype form assembly are intended to enable the user to maximize the rehabilitation function independently with the help of soft robotic glove containing the PBA.

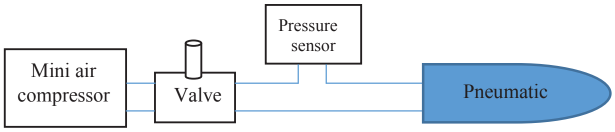


Fig. 9. PBA pneumatic network system

IV. RESULT AND DISCUSSION

There were two kinds of tests on the soft PBA, the first was giving the pressurized air to the PBA when unattached and the second was giving the pressurized water to the PBA attached on the human finger. In this test, the length of the hose from the mini air compressor to the soft PBA was 100 cm. Embedded system in this test was conducted by using Arduino Support from Simulink. This toolbox can be download freely on MathWorks website. The pressure data retrieval process was performed for 40 seconds. The input value varied in the bending test process of the soft PBA was the PWM value of the mini motor air compressor input. The larger the given PWM, the speed of the mini-air compressor motor rotation will be faster. This pneumatic network system used a power supply of 12 V. In this test. The PWM input value given to the mini air compressor varied from 140 to 160. The PWM value that can be applied to the mini air compressor was from 0 to 255. The maximum PBA pressure can be determined by several tests. When it was tested, the maximum pressure value on PBA was 123 kPa. The value was obtained from the average pressure value when PBA broke or leaked. In order not to leak the PBA, the maximum allowable pressure on PBA was 110 kPa.

The result of pressure test on the soft PBA when given variation of PWM input on mini air compressor can be shown in Fig. 10., and Fig. 11. Based on the results of the test, the pressure response on the soft PBA shows that there is no significant difference between PBA unattached on the finger and PBA attached on the human finger.

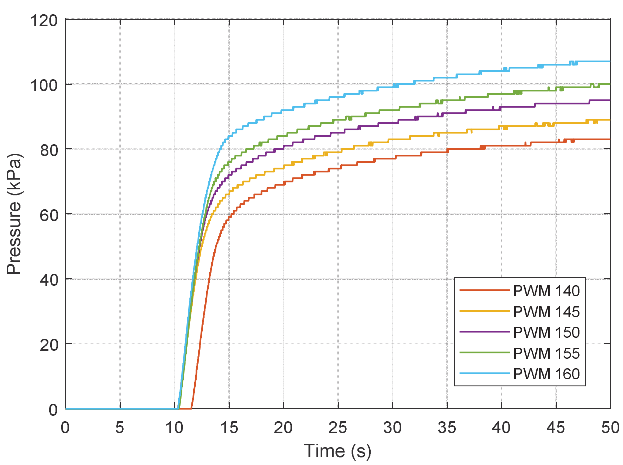


Fig. 10. Pressure response with respect to PWM input unattached on the finger

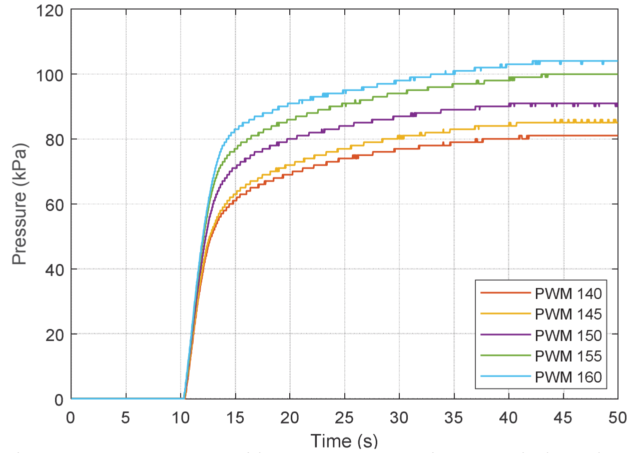
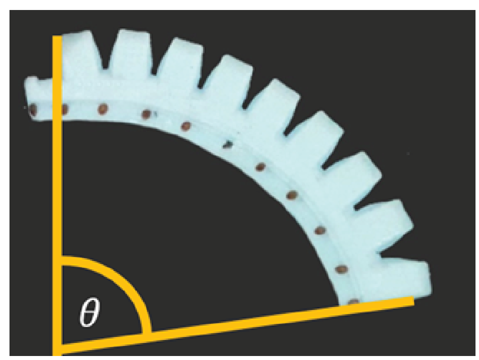


Fig. 11. Pressure response with respect to PWM input attached on the finger

When the PBA is supplied with compressed air, the pressure causes the indentation of the soft PBA. The resulting indentation is a form of flexion such as when it moves on a human finger. The process of collecting bend angle of PBA data in this study follows the steps performed by Polygerinos [8]. Figure 12.a shows the bending that occurs when the PBA attached in the human finger. Figure 12.b shows the curve of the PBA when it attached to the human finger.



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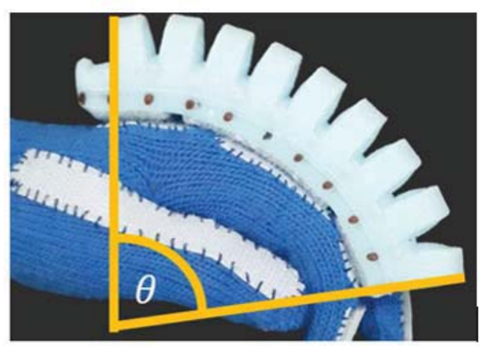

(b)

Fig. 12. Bending angle on PBA (a) Unattached (b) Attached on the finger

The result of bending angle on the soft PBA when given by variation of pressure input can be shown in Fig. 13. and Fig. 14. Based on the test results, the bending angle on the soft PBA shows that the bending angle of unattached PBA on the human finger has higher bending angle than the PBA attached on the human finger as summarized in Fig. 15. Fig.

16 shows the prototype of the proposed PBA on the soft glove accompanied by a hardware system. Finally, the soft exoskeleton glove is built and implemented on the human healthy hand to assist a human in grasping an object. For the future research, the soft glove will be used for assisting the human hand in activity of daily living (ADL).

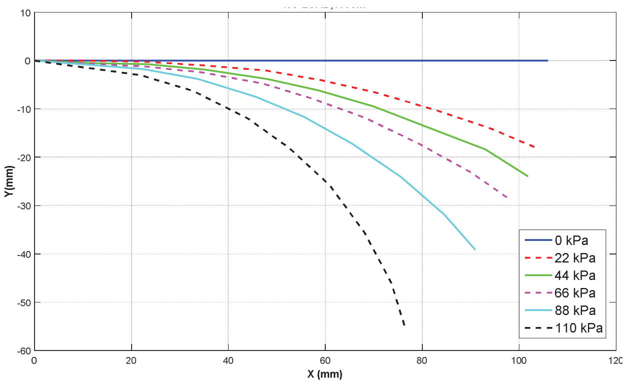

Fig. 13. Bending angle on PBA unattached on the finger

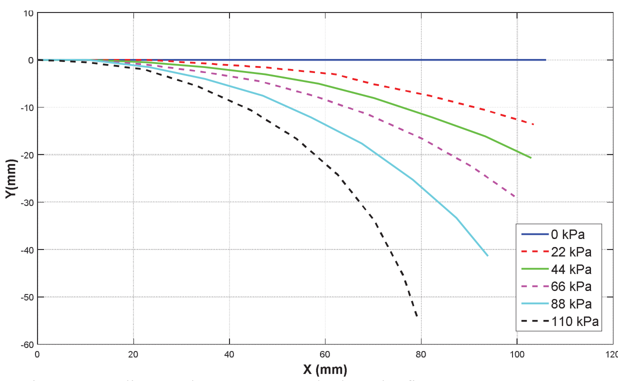

Fig. 14. Bending angle on PBA attached on the finger

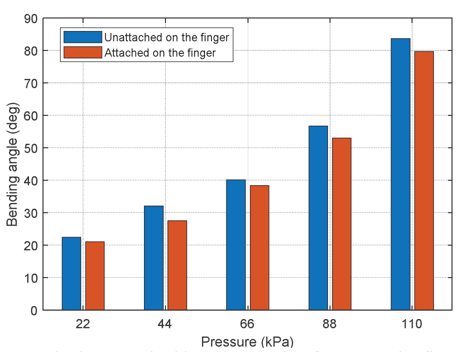

Fig. 15. Unattached vs attached bending angle of PBA on the finger


Fig. 16. Result of the final PBA prototype

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REFERENCES

[1] R. Ismail, M. Ariyanto, K. A. Pambudi, J. W. Syafei, and G. P. Ananto, “Extra robotic thumb and exoskeleton robotic fingers for patient with hand function disability,” in *2017 4th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI)*, 2017, pp. 1–6.

[2] D. Rus and M. T. Tolley, “Design, fabrication and control of soft robots,” *Nature*, vol. 521, no. 7553, pp. 467–475, May 2015.

[3] H. K. Yap, Jeong Hoon Lim, F. Nasrallah, J. C. H. Goh, and R. C. H. Yeow, “A soft exoskeleton for hand assistive and rehabilitation application using pneumatic actuators with variable stiffness,” in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, 2015, pp. 4967–4972.

[4] P. Polygerinos *et al.*, “Towards a soft pneumatic glove for hand rehabilitation,” in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2013, pp. 1512–1517.

[5] H. K. Yap, J. C. H. Goh, and R. C. H. Yeow, “Design and Characterization of Soft Actuator for Hand Rehabilitation Application,” in *6th European Conference of the International Federation for Medical and Biological Engineering*, Springer, Cham, 2015, pp. 367–370.

[6] P. Maeder-York *et al.*, “Biologically inspired soft robot for thumb rehabilitation,” *J. Med. Devices Trans. ASME*, vol. 8, no. 2, p. 020933, 2014.

[7] Y. Kadowaki, T. Noritsugu, M. Takaiwa, D. Sasaki, and M. Kato, “Development of Soft Power-Assist Glove and Control Based on Human Intent,” *J. Robot. Mechatron.*, vol. 23, no. 2, pp. 281–291, Apr. 2011.

[8] P. Polygerinos *et al.*, “Modeling of Soft Fiber-Reinforced Bending Actuators,” *IEEE Trans. Robot.*, vol. 31, no. 3, pp. 778–789, Jun. 2015.