Jurnal Inovasi Teknologi dan Rekayasa
Vol. 8, No. 2, July-December 2023, pp. 225-232

Comparative Analysis of Soft Pneumatic Actuator Designs for Effective Human Finger Movement: A Study on Continuous and Non-Continuous Chamber Configurations

Syahirul Alim Ritonga [a,1,*], Herianto [b,2]

[a,b] *Universitas Gadjah Mada, Jl. Grafika, Sinduadi, Mlati, Sleman (55281), Indonesia*
[1] *syahirul.alim.r@mail.ugm.ac.id*; [2]*Herianto@ugm.ac.id;*

ARTICLE INFO

Article history:
Accepted

Keywords:
Soft pneumatic actuator
Robot
Design
3D print

ABSTRACT

Soft actuators show immense potential in various fields, such as wearable medical devices and the rehabilitation of stroke patients. This study aims to design and fabricate a soft pneumatic actuator (SPA) that effectively mimics human finger movements, with specific focus on post-stroke rehabilitation. Two SPA designs, referred to as M1 and M2, were developed and compared. M1 featured segmented chambers to mimic finger joints, while M2 had continuous chambers. The performance of the SPAs was evaluated based on curvature, generated force, and similarity to natural finger movement. Results showed that M1 exhibited superior curvature and achieved greater bending angles compared to M2 at the same pressure levels. This makes M1 well-suited for applications requiring high bending angles such as gripping. Additionally, M2 demonstrated the ability to mimic specific angles associated with picking-like movements. The findings highlight the potential for further research to explore the customization of SPAs for specialized tasks by modifying the number of sections and chambers. In terms of force, M2 generated slightly higher forces than M1, although the difference was not statistically significant. Overall, it is expected that this research contributes to the development of soft actuators and wearable medical devices, particularly in the field of post-stroke rehabilitation.

I. Introduction

Soft actuators have emerged as a promising alternative to conventional actuators, offering significant advantages in addressing a wide range of previously challenging applications [1-2]. These actuators are fabricated using soft materials, endowing them with remarkable flexibility and elasticity [3-4]. As a result, they are well-suited for applications that involve restricted spaces, dynamic environments, gentle interactions, and direct human involvement [1,3]. Their distinctive attributes enable them to operate with minimal impact on their surroundings, ensuring safe and efficient utilization across diverse fields.

Soft actuators are classified based on their method of movement, which can involve wire, smart materials, or electricity [5]. Among the different types of soft actuators, the soft pneumatic actuator (SPA) is particularly popular, utilizing pressurized air to drive its motion. SPAs are renowned for their affordability, user-friendliness, and exceptional performance [5-7].

Soft actuators show tremendous potential in the field of wearable medical devices, particularly in the domain of post-stroke rehabilitation [8]. These innovative devices require precise control over movement and force, as they directly interface with patients. Conventional actuator technologies, such as servos and motors, present significant risks in such applications, necessitating complex safety measures to prevent harm to patients in the event of uncontrolled movements. However, the utilization of soft actuators, specifically soft pneumatic actuators (SPAs), offers a

DOI: 10.31572/inotera.Vol8.Iss2.2023.ID243 W : http://inotera.poltas.ac.id | E : inotera@poltas.ac.id

compelling solution. With their inherent high flexibility and elasticity, SPAs ensure that uncontrolled movements pose no threat to patient well-being. Consequently, integrating SPAs into post-stroke rehabilitation devices provides a safer and more secure option for patients.

Previous research endeavors have made notable strides in incorporating soft actuators into wearable medical devices, post-stroke rehabilitation devices, and assistive gloves [9-12]. However, the majority of these studies have focused on designing soft actuators with continuous chambers which means that all of the part of SPA can be bent, overlooking the specific anatomical features of the human finger, such as knuckles and joints. To date, there remains a dearth of investigations dedicated to developing soft actuators that accurately mimic the intricate shape and functionality of the human finger. This research gap highlights the need for a novel approach in designing soft actuators that can replicate the natural characteristics of human finger movements and enhance their applicability in various fields.

This study aims to design and fabricate a soft pneumatic actuator (SPA) specifically tailored to enable effective human finger movement, with a focus on its potential application in post-stroke rehabilitation. The SPA will be designed to closely resemble the anatomical shape of a human finger. The performance of the SPA will be evaluated based on three key metrics: curvature, force, and similarity to natural finger movement. These assessments will provide valuable insights into the SPA's ability to replicate the intricate motion patterns of a human finger, paving the way for its potential use in rehabilitation therapies for individuals recovering from stroke.

In this study, the fabrication of the SPA will be carried out using 3D printing, also known as additive manufacturing. This method offers numerous advantages over traditional fabrication techniques, including cost-effectiveness, a rapid manufacturing process, and greater flexibility in design possibilities [7], [13-15]. By utilizing 3D printing, the SPA can be customized to meet the specific requirements of individual patients, ensuring a tailored and personalized approach. Additionally, the fast-manufacturing time associated with 3D printing enables efficient production of the SPA, making it a suitable choice for applications where timely fabrication is crucial.

The findings of this research are anticipated to make contributions to the advancement of soft actuators and wearable medical devices, specifically in the field of post-stroke rehabilitation. By exploring and understanding the behavior and performance of soft actuators, this research aims to enhance their effectiveness and applicability in assisting stroke patients during their rehabilitation process. The insights gained from this study can inform the design and development of innovative wearable devices that promote patient recovery and improve their quality of life. Ultimately, the research outcomes have the potential to drive advancements in the field of rehabilitation technology and contribute to the overall well-being of stroke patients.

II. Method

This research employed an experimental methodology to investigate the effectiveness of two different SPA designs. To measure the curvature of the SPA, an image processing software was utilized. The detail method will be elaborated in this section.

A. Observing Human Finger

Prior to designing the SPA, the dimensions and bending angles of the researcher's finger were measured. These measurements were based on various movements commonly performed by rehabilitation therapists to aid stroke patients, including gripping, grasping, and picking-like movements [16-17]. The therapist's movements served as a reference for accurately capturing the finger dimensions to ensure the SPA design closely mimicked natural finger movements.

The measurement process involved capturing a photograph of the finger, which was subsequently processed using image processing software, as shown in Figure 1. This allowed for accurate analysis of the finger's dimensions and bending angles. The obtained measurements served as reference values for evaluating the performance of the fabricated SPA. The corresponding dimension and bending angle data are presented in Table.

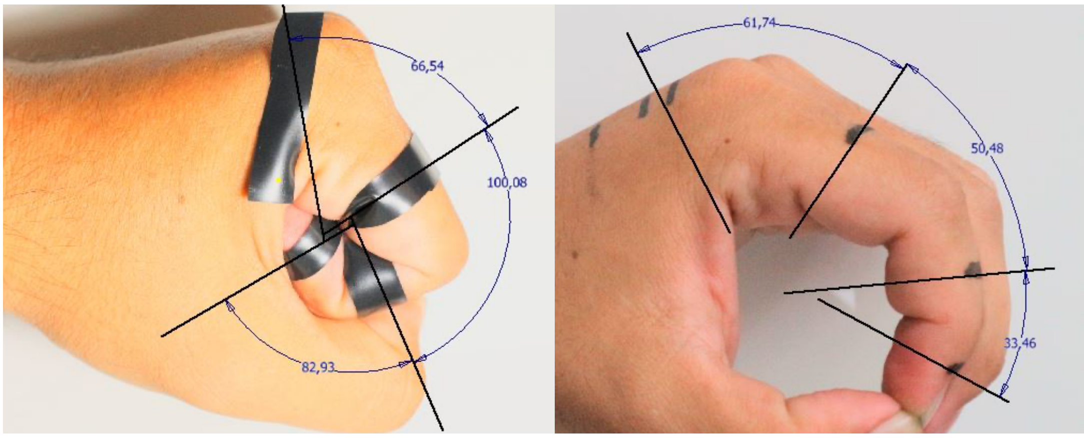

Fig. 1. The measurement of the curvature finger joints in real life application. A. Picking-like movement B. Grasping [18]

Table 1. The angles of finger joints of human in real application

The Joint Angles of Human Fingers During Grasping Movements		
Joints	Angles	
	Grasping	Picking-like
MP	66.53	61.74
PIP	100.08	50.48
DIP	82.93	33.46

B. SPA Design

In this research, two different designs, namely M1 and M2, were tested and evaluated, as depicted in Figure 2. SPA type M2 was fabricated with a continuous chamber configuration, hypothesized to exhibit a larger bending angle. Conversely, SPA type M1 was designed with separators after several chambers to mimic the shape of a human finger and accommodate its knuckles. The chambers play a crucial role in enabling bending motion, as the difference in elasticity between the upper and bottom sides of the chambers is influenced by their geometric variations. Additionally, each SPA featured an inlet part at the beginning, serving as a channel for the pressurized air flow.

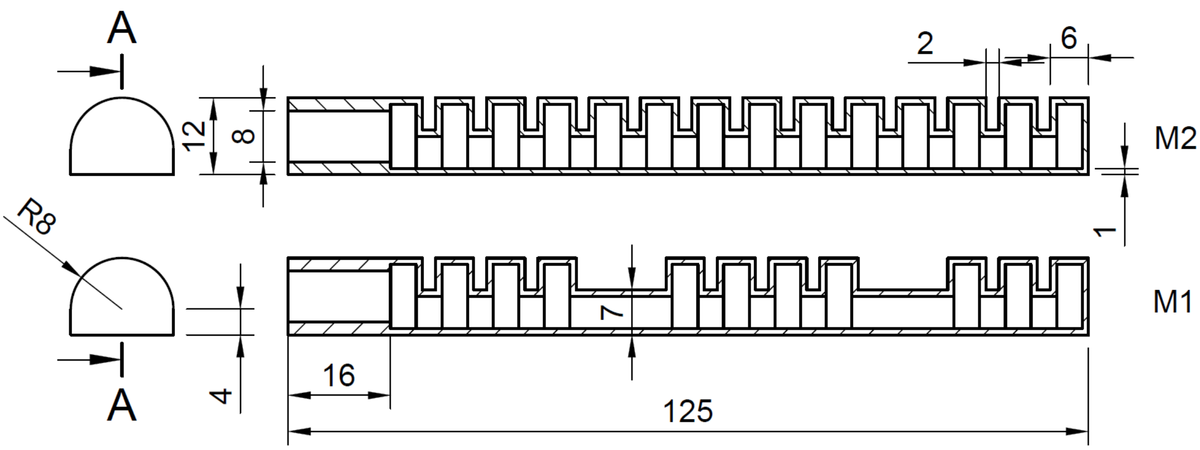

Fig. 2. The design of two types of samples, M1 and M2

In this research, the independent variable was the type of SPA, specifically SPA type M1 and SPA type M2. The dimensions of all SPAs were kept consistent to ensure a fair comparison. As depicted in Figure 2, the total length of each SPA was 125 mm, with each chamber having a length of 6 mm. The chamber thickness was maintained at 1 mm for all SPAs. These standardized dimensions allowed for a controlled evaluation of the performance differences between the two SPA types.

The difference point was on the number of chambers, SPA type M2 was designed with a total of 14 chambers distributed along its length. In contrast, SPA type M1 was specifically structured with three group of chambers to mimic the knuckles of the human finger which consisted of: the metacarpophalangeal (MCP) joint, the proximal interphalangeal (PIP) joint, and the distal interphalangeal (DIP) joint. The MCP and PIP joints of SPA type M1 each contained 4 chambers, while the DIP joint consisted of 3 chambers. This variation in the number of chambers reflected the bending characteristics of each joint, with the DIP joint having a smaller degree of bending compared to the MCP and PIP joints.

C. SPA Fabrication

The fabrication of the SPAs was carried out using the 3D printing method. Specifically, a FDM 3D Printer (Core XY, DIY) was used in this research, along with TPU Eflex filament (ESun) as the printing material. The TPU Eflex material has a melting point of 190°C. Prior to printing, the design of the SPAs was created using CAD software and sliced using Ultimaker Cura to generate the G-Code file required by the 3D Printer. The printing process employed various parameters and remained constant for two tested designs, which are detailed in Table 2.

Table 2. Printing Parameters

Printing parameters	
Infill	100%
Speed	30 mm/s
Print Temperature	230^o C
Layer thickness	0.1 mm
Flow Rate	130%
Fan speed	0

Fig. 3. The SPAs were inflated and measured. A. Unloaded M1. B. Unloaded M2 C. The loaded SPA. [18]

D. Measurement and Analysis

The measurements were performed under two different conditions, as shown at Figure 3. The first measurement involved the SPAs being moved without any external load applied. In contrast, the second measurement was conducted with the SPAs attached to a passive finger. This created a loading condition where the SPAs were solely responsible for actuating the finger. Consequently, the obtained results represented the curvature of the finger induced by the SPAs without any additional external factors but the inertia of the finger.

The bending angle was measured by using image processing software, imageJ. The curvature of each joint was measured and compared with the curvature of real movement of finger that has been measured before. To reduce the bias due to the difference number of SPA, the finger’s joint was made as reference point rather than the SPA itself.

To evaluate the performance of the SPAs, the generated forces at each joint were measured. This was accomplished by attaching a force-scale to each joint of the SPA. For this purpose, a specially designed hook made using 3D Printing was utilized. A thread was employed to transmit the force from each joint to the hook. Consequently, when a joint was subjected to pressurized air and attempted to bend, the hook prevented the bending movement, resulting in a reaction force exerted on the hook, which was then measured by the force-scale, as shown in Figure 4. This procedure was repeated three times for each joint to obtain reliable and consistent results.

Fig. 4. The measurement of force generated by each joint of SPA.[18]

III. Result and Discussion

A. The Curvature of SPA

The experimental results are presented in Table 3 and Figure 5, which displays the measured curvature of the samples when pressurized air was applied. Two sets of measurements were conducted. The first set, shown in Table 3(A), represents the curvature of the SPAs without any external load attached, allowing them to bend freely. On the other hand, Table B) illustrates the curvature of the SPAs when they were attached to a passive finger which acted as a load in the experiment.

Based on the data presented in Table 3 it appears that SPA type M2 exhibits superior elasticity compared to type M1. This can be attributed to the larger total bending angle achieved by type M2 at the same applied air pressure. In the unloaded condition (Table A), type M1 achieved bending angles of 167°, 200°, and 238° at 2, 2.5, and 3 bars respectively. In contrast, type M2 already reached a bending angle of 360° at 2 bars, indicating its greater flexibility. It is worth noting that the bending angle for type M2 could potentially exceed 360° if not limited by the inlet part itself. A similar trend is observed in the measurements conducted under load (Table B). Type M1 exhibited bending angles of 127°, 155°, and 163° at 2, 2.5, and 3 bars respectively, while type M2 achieved bending angles of 174°, 198°, and 227°.

The results suggest that there is a tendency for type M2 to outperform type M1 in terms of bending ability. This observation may be attributed to the difference in the number of chambers between the two types, potentially contributing to the enhanced elasticity and flexibility of M2 compared to M1. Consequently, it appears that M2 has the potential to be more suitable for tasks requiring a higher bending angle, such as grasping and gripping.

Table 3. The result of experiment

Curvature Without Load				
	Joint	**Pressure (Bar)**	**Curvature of M1 (°)**	**Curvature of M2 (°)**
1	MP	2	62	
2	PIP	2	65	
3	DIP	2	40.26	
	Total		**167.26**	**>360**
4	MP	2.5	74.58	
5	PIP	2.5	75	
6	DIP	2.5	51.14	
	Total		**200.72**	**>360**
7	MP	3	88	
8	PIP	3	89.17	
9	DIP	3	61	
	Total		**238.17**	**>360**

Curvature With Load (Attached to The Finger)				
	Joint	**Pressure (Bar)**	**Curvature of M1 (°)**	**Curvature of M2 (°)**
1	MP	2	37.49	63.5
2	PIP	2	52	59.92
3	DIP	2	37.42	51
	Total		**126.91**	**174.46**
4	MP	2.5	53.15	69.06
5	PIP	2.5	56	73.2
6	DIP	2.5	46	55.8
	Total		**155.15**	**198.06**
7	MP	3	59.79	83.71
8	PIP	3	57.65	83.52
9	DIP	3	46	60
	Total		**163.44**	**227.22**

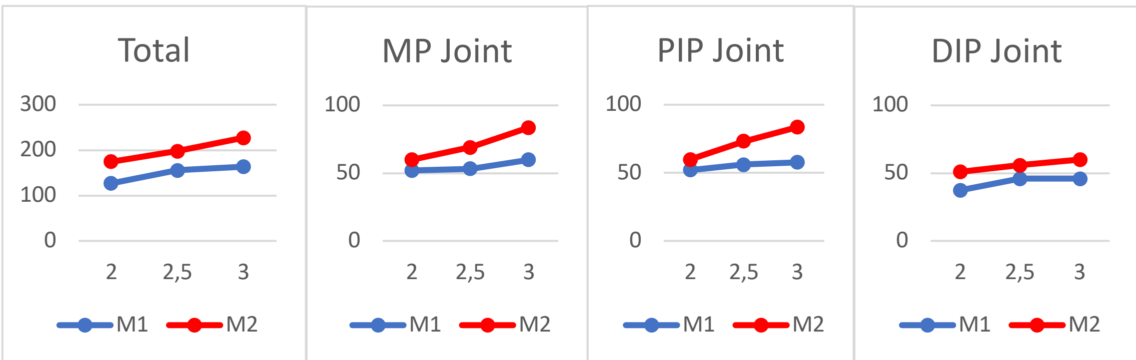

Fig. 5. The result in the graphic form

B. Comparing with Human's Finger

However, it is noteworthy that in the experiment presented in Error! Reference source not found., the loaded M1 exhibited a closer resemblance to the shape of a human finger during the picking-like movement, as demonstrated in Table Specifically, at 3 bars of pressure, the bending angle of M1 closely matched that of a real finger performing the picking movement. This finding suggests that the M1 design, with its non-continuous segmented parts, has the potential to provide the necessary force for achieving the required angle. Consequently, this result offers intriguing possibilities for utilizing the M1-type SPA in applications that demand a specific finger movement pattern. However, further research and validation are needed to fully explore the suitability and practicality of this design in such applications.

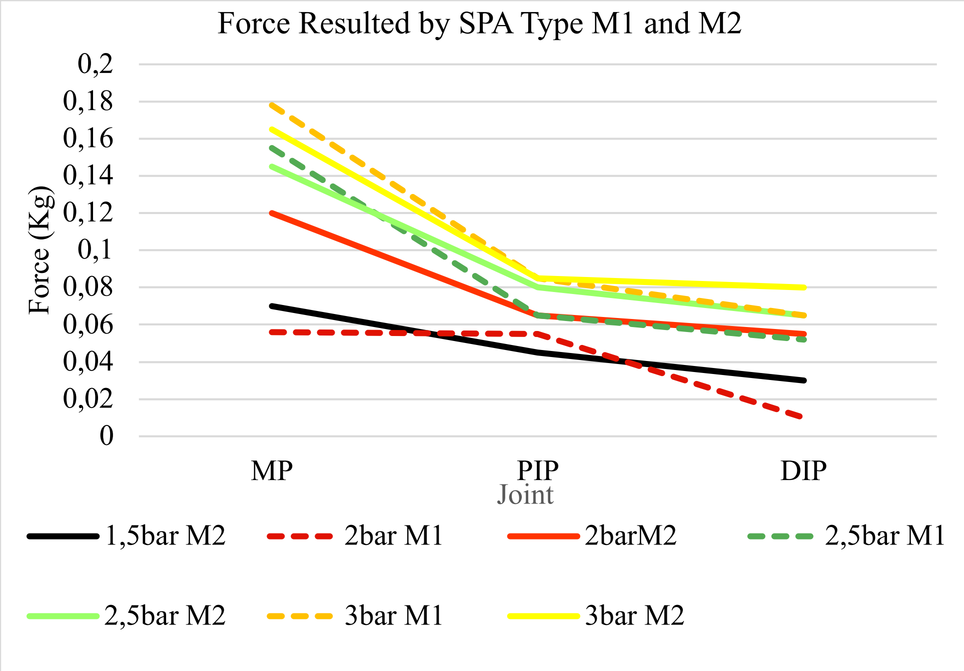

Fig. 1. Comparison of force generated by two types of SPAs

C. Generated Force

From the Figure 6**,** it can be observed that design M2 consistently generated slightly higher forces compared to M1 at the same pressure levels. The overall trend is clear and consistent, with M2 demonstrating a slight advantage. However, it is important to note that there were a few anomalies, such as at 3 and 2.5 bars at the MP joint where M1 produced slightly higher forces than M2. Moreover, the differences were minor and not statistically significant. Therefore, it is not appropriate to definitively state that one particular type of SPA was superior to the other in terms of force generation.

IV. Conclusion

In conclusion, this research aimed to identify the optimal design of a soft pneumatic actuator (SPA) for mimicking finger movements. Two designs, M1 and M2, were fabricated and inflated using pressurized air. The key difference between the designs was the continuity of chambers, with M2 featuring segmented chambers along its body and M1 incorporating gaps to separate the chamber, which aimed to mimic finger joints. The findings revealed that M1 exhibited superior curvature and achieved greater bending angles compared to M2 at the same pressure levels. Therefore, M1 is more suitable for applications that require high bending angles such as gripping and grasping. On the other hand, M2 demonstrated the ability to mimic specific angles produced by real fingers, such as in picking-like movements. This characteristic is particularly intriguing and warrants further exploration to develop SPAs capable of performing specialized tasks that require specific shapes by modifying the number of sections and chambers in each section. In terms of force, M2 exhibited slightly higher force values than M1, although the difference was minor and not statistically significant.

I. References

[1] C. Tawk and G. Alici, "A Review of 3D-Printable Soft Pneumatic Actuators and Sensors: Research Challenges and Opportunities," *Advanced Intelligent Systems*, vol. 3, no. 6, p. 2000223, 2021, doi: 10.1002/aisy.202000223.

[2] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, pp. 467–475, 2015, doi: 10.1038/nature14543.

[3] A. D. Marchese, R. Tedrake, and D. Rus, "Dynamics and trajectory optimization for a soft spatial fluidic elastomer manipulator," *International Journal of Robotics Research*, vol. 35, no. 8, pp. 1000–1019, 2016, doi: 10.1177/0278364915587926.

[4] N. Tan, X. Gu, and H. Ren, "Design, characterization and applications of a novel soft actuator driven by flexible shafts," *Mech Mach Theory*, vol. 122, pp. 197–218, 2018, doi: 10.1016/j.mechmachtheory.2017.12.021.

[5] G. M. Whitesides, "Soft Robotics," *Angewandte Chemie - International Edition*, vol. 57, no. 16, pp. 4258–4273, 2018, doi: 10.1002/anie.201800907.

[6] M. Zolfagharian, A., Denk, M., Bodaghi, "Topology-Optimized 4D Printing of a Soft Actuator," *Acta Mech. Solida Sin.*, vol. 33, pp. 418–430, 2020, doi: https://doi.org/10.1007/s10338-019-00137-z.

[7] H. K. Yap, H. Y. Ng, and C. H. Yeow, "High-Force Soft Printable Pneumatics for Soft Robotic Applications," *Soft Robot*, vol. 3, no. 3, pp. 144–158, 2016, doi: 10.1089/soro.2016.0030.

[8] C. Tefertiller, B. Pharo, N. Evans, and P. Winchester, "Efficacy of rehabilitation robotics for walking training in neurological disorders:A review," *J Rehabil Res Dev*, vol. 48, no. 4, pp. 387–416, 2011, doi: 10.1682/JRRD.2010.04.0055.

[9] M. Cianchetti, C. Laschi, A. Menciassi, and P. Dario, "Biomedical applications of soft robotics," *Nat Rev Mater*, vol. 3, no. 6, pp. 143–153, 2018, doi: 10.1038/s41578-018-0022-y.

[10] C. Thalman and P. Artemiadis, "A review of soft wearable robots that provide active assistance: Trends, common actuation methods, fabrication, and applications," *Wearable Technologies*, vol. 1, pp. 1–27, 2020, doi: 10.1017/wtc.2020.4.

[11] H. K. Yap, J. H. Lim, F. Nasrallah, J. Cho Hong Goh, and C. H. Yeow, "Characterisation and evaluation of soft elastomeric actuators for hand assistive and rehabilitation applications," *J Med Eng Technol*, vol. 40, no. 4, pp. 199–209, May 2016, doi: 10.3109/03091902.2016.1161853.

[12] B. Mosadegh *et al.*, "Pneumatic Networks for Soft Robotics that Actuate Rapidly," pp. 2163–2170, 2014, doi: 10.1002/adfm.201303288.

[13] K. J. Cho, J. S. Koh, S. Kim, W. S. Chu, Y. Hong, and S. H. Ahn, "Review of manufacturing processes for soft biomimetic robots," *International Journal of Precision Engineering and Manufacturing*, vol. 10, no. 3, pp. 171–181, 2009, doi: 10.1007/s12541-009-0064-6.

[14] J. Z. Gul *et al.*, "3D printing for soft robotics–a review," *Sci Technol Adv Mater*, vol. 19, no. 1, pp. 243–262, 2018, doi: 10.1080/14686996.2018.1431862.

[15] R. F. Wallin, T.J., Pikul, J. & Shepherd, "3D printing of soft robotic systems," *Nat Rev Mat*, vol. 3, pp. 84–100, 2018, doi: https://doi.org/10.1038/s41578-018-0002-2.

[16] K. C. Lin, C. Y. Wu, T. H. Wei, C. Y. Lee, and J. S. Liu, "Effects of modified constraint-induced movement therapy on reach-to-grasp movements and functional performance after chronic stroke: A randomized controlled study," *Clin Rehabil*, vol. 21, no. 12, pp. 1075–1086, Dec. 2007, doi: 10.1177/0269215507079843.

[17] N. Friedman *et al.*, "Retraining and assessing hand movement after stroke using the MusicGlove: comparison with conventional and therapy and isometric grip training," *J Neuroeng Rehabil*, 2014, Accessed: May 30, 2023. [Online]. Available: 10.1186/1743-0003-11-76.

[18] Syahirul Alim Ritonga, "Analysis of The Effect of Dimensions, Number of Chambers, and Geometry on Strength and Curvature of 3D Printed Soft Pneumatic Actuator As a Stroke Rehabilitation Glove," Bachelor Thesis, Universitas Gadjah Mada, Yogyakarta, 2019.