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Comparative Analysis of Custom-Designed Soft Pneumatic Actuators for Human Thumb Movement in Post-Stroke Rehabilitation

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ABSTRACT

One of the most potential applications of soft actuator is as wearable medical devices for post-stroke rehabilitation as a field that requires high levels of safety and adaptability. Incorporating SPAs into such devices can provide a safer and more secure solution, ensuring controlled movements that do not pose a risk to patients. However, there is a research gap regarding the design considerations for soft actuators specifically targeting the human thumb, which exhibits distinct motion patterns compared to the other fingers. This paper addresses this gap by developing and evaluating custom-designed SPAs for the movement of the human thumb, with a focus on post-stroke rehabilitation. Three SPA models (M1, M2, and M3) were proposed, and their performance in replicating the twisting motion of the thumb was assessed. The SPAs were fabricated using 3D printing, and image processing software was utilized for measurement and analysis. The results showed that the M3 model, with two sections of chambers in different axes, exhibited the best performance in generating the desired twisting angle. Integration of the M3 model with four finger-shaped SPAs enabled successful grasping and picking-like movements. This research contributes to the advancement of soft actuators in wearable medical devices, particularly in post-stroke rehabilitation, and holds promise for enhancing patient recovery and quality of life.

I. Introduction

In recent years, the development of soft actuators has emerged as a solution to address various challenges that conventional actuators, such as motor and servo, cannot overcome [1-3]. The development of soft actuators was inspired by biological movements, characterized by flexibility and compliance, which are enabled by the implementation of its soft materials and unique structures [1], [4-7]. Its softness and flexibility, made soft actuator potentially outperforming conventional actuators in several applications that involving dynamic environments, narrow space, and contacting with living organism [3-4]. Their distinctive attributes enable them to operate with minimal impact on their surroundings, ensuring safe and efficient utilization across diverse fields.

Soft pneumatic actuator is one of category of soft actuator that actuated by using pneumatic which is usually in the form of pressurized air [8]. Soft pneumatic actuator is widely used due to its ease to operate and good performance [8-10]. Pressurized air is easy to find in various labs and industries, clean, and low cost [11-12]. Moreover, its performance is good compared with other type of soft actuators, in term of the generated curvature and force [11,13].

Numerous research has studied the potential application of soft actuator, among them are their potential as minimally invasive surgery, locomotion, gripper and grasper [3, 12], [14-18]. One of the potential applications of soft actuator is in wearable medical device, particularly in the area of post-stroke rehabilitation. This field require high safety, considering that the device will contact with patient's hands and move them. Using conventional actuators in this application can be risky, since uncontrolled movement can harm the patient. However, the softness and flexibility of soft actuator can suit and be a solution for this application. By incorporating SPAs into post-stroke rehabilitation devices, patients can benefit from a safer and more secure solution, as SPAs guarantee that uncontrolled movements do not pose a risk to their well-being.

Previous research has made attempts to incorporate soft actuators into various applications, including wearable medical devices, post-stroke rehabilitation devices, and assistive gloves [19-22]. However, the majority of these studies have predominantly focused on the design of finger-like soft actuators and less investigation had been done on the specific design considerations for the human thumb. This research gap highlights the necessity for a novel approach in the design of soft actuators that accurately emulate the natural characteristics of human thumb movements. By addressing this gap, the potential applications of soft actuators can be expanded across diverse fields.

The objective of this research is to develop and manufacture a custom-designed soft pneumatic actuator (SPA) that facilitates the movement of the human thumb, with a specific focus on its potential application in post-stroke rehabilitation. The SPA will be carefully engineered to closely mimic the natural anatomical movement of a human thumb. The performance evaluation of the SPA will primarily concentrate on two key aspects: curvature and similarity to natural thumb movement. These evaluations will provide valuable insights into the SPA's ability to accurately replicate the intricate motion patterns of the human thumb. This investigation lays the groundwork for potential integration of the SPA in rehabilitation therapies aimed at assisting individuals in their stroke recovery journey.

In this research, the fabrication of the SPA will be carried out using 3D printing, also known as additive manufacturing. This technique presents numerous advantages over conventional fabrication methods, such as cost-effectiveness, expedited manufacturing process, and enhanced design flexibility [10]. Additionally, the quick production time associated with 3D printing enables efficient manufacturing of the SPA, making it conducive for iterative testing and maintaining a low overall cost.

The results of this research are expected to have significant implications for the progress of soft actuators and wearable medical devices, particularly in the domain of post-stroke rehabilitation. By investigating and comprehending the behavior and performance of soft actuators, this study aims to enhance their efficacy and suitability in aiding stroke patients throughout their rehabilitation journey. The knowledge gained from this research can inform the design and advancement of wearable devices that facilitate patient recovery and enhance their quality of life. Ultimately, the outcomes of this research have the potential to propel advancements in rehabilitation technology and contribute to the overall well-being of individuals recovering from stroke.

II. Method

This research employed an experimental approach to evaluate and compare three models of SPA in terms of their ability to replicate the motion of the human thumb. The effectiveness of each model was assessed through careful analysis. To measure the curvature of the SPAs, image processing software was utilized. The subsequent section will provide a comprehensive discussion on the specific methodology employed in this research.

A. Observing Human Thumb

Before evaluate the SPA, the researcher took measurements of their own thumb’s dimensions and bending angles, as shown in Figure 1. These measurements were based several movements that commonly performed by rehabilitation therapists to assist stroke patients, such as gripping, grasping, and picking-like actions [23-24]. There are three joints in human’s thumb, they are carpometacarpal (CMC), metacarpophalangeal (MP), and interphalangeal (IP).

The measurement process involved capturing a photograph of the finger, which was then processed using image processing software, which was Image J (the accuracy up to 98,5%). This enabled accurate analysis of the finger's dimensions and bending angles. The measurements obtained from this process were used as reference values to assess the performance of the created SPA.

From the measurement, it appears that the twisting angle required by thumb is 102.65-31.12=70.53°.

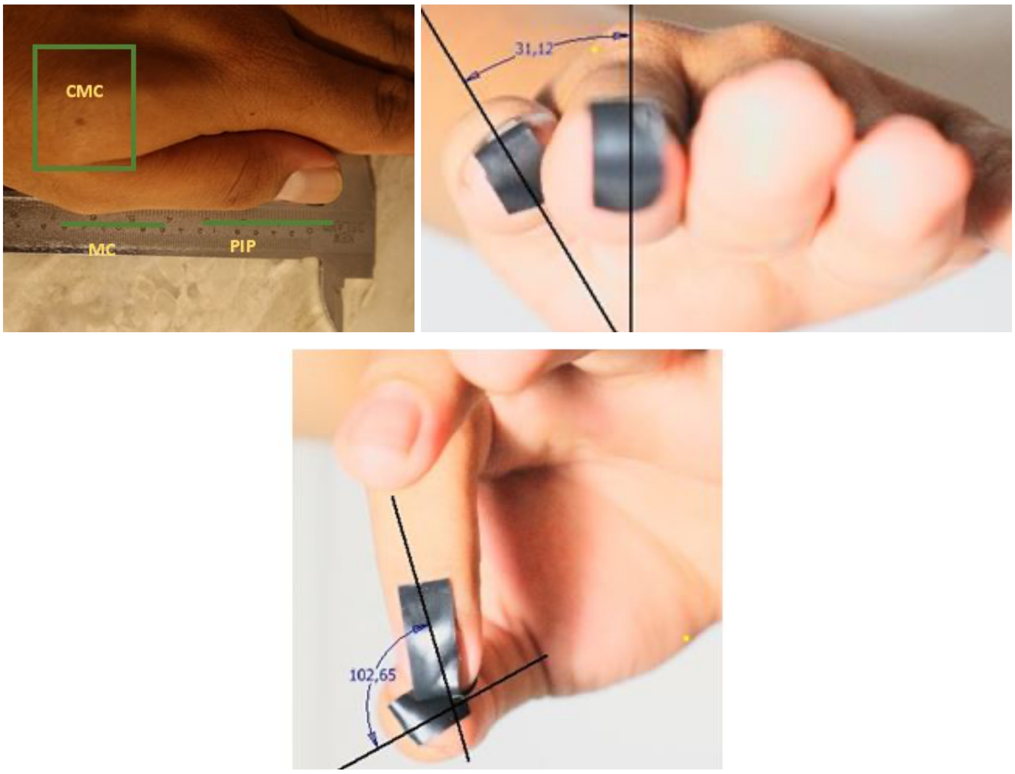

Fig. 1. The measurement of real thumb movement

B. SPA Samples Design

From observing human thumb movement, it was obtained that human's thumb, unlike other four fingers, move in two axes when conducting the movements such as gripping, grasping, and picking-like actions. To mimic that motion, three models were proposed in this research, they are M1, M2, and M3, as can be seen in Figure 2.

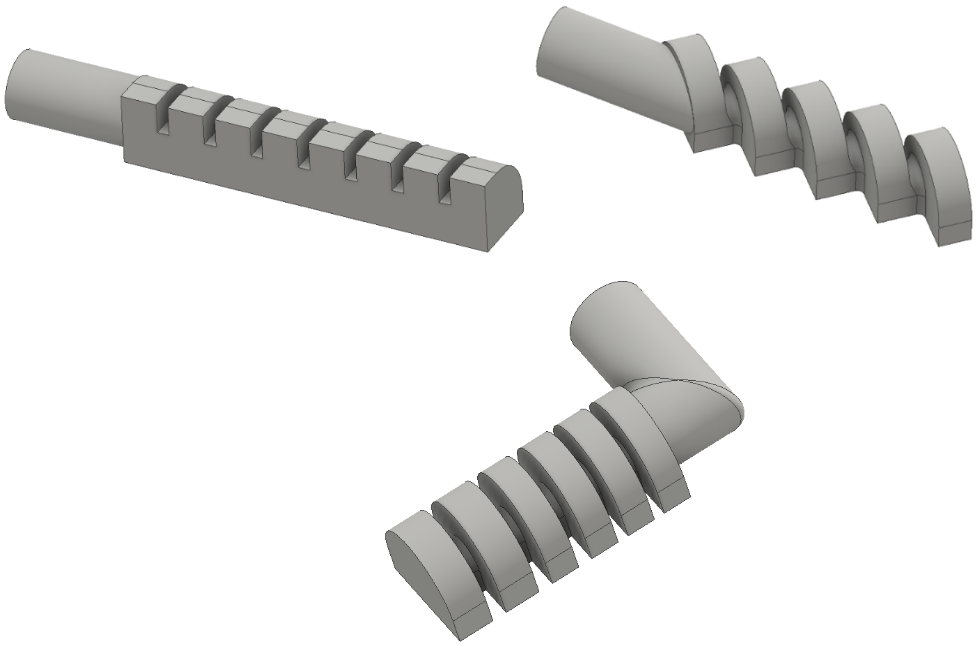

Fig. 2. The proposed design, M1, M2, and M3.

The three models were developed based on the concept of PneuNets, which leverage the differential elasticity between the elastic layer on the top side of the SPA and the rigid layer at the bottom side to enable bending. The top layer attains increased elasticity due to its structure, which comprises chambers.

M1 was developed using an SPA design with two rigid layers positioned along the x and y axes. The objective was to enable movement in two axes to closely mimic the natural motion of the human thumb.

M2 was designed with the axis of chambers twisted at a 45-degree angle. The intention behind this design was to facilitate bending in the form of twisting, combining movement along two axes.

M3 incorporated a combination of chambers in two axes. The first region consisted of multiple chambers arranged along the x-axis, while the second region comprised several chambers arranged along the y-axis. A rigid layer served as a turning point between the first and second regions.

All of the three models were created by using the similar number of chambers and similar length of chamber, they are 6 chambers and 4 mm length.

C. SPA Fabrication

SPAs were fabricated by using 3D Printing method, specifically with FDM 3D Printing (Core XY, DIY). The material that used in this research was TPU Eflex filament (eSun eFlex). Eflex is chosen in this research because its hyperelastic characteristic suit with the application of SPA, good outcome, commercially available in the market, and commonly used in 3D Printing communities [25]–[27]. 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 result quality is heavily affected by it printing parameters which are shown in Table 1.

Table 1. Printing parameters of the SPA

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

D. Measurement and Analysis

During the measurement process, the SPAs were subjected to controlled bending by inflating them with pressurized air at 2, 2.5, and 3 bars, as shown in Fig 3. Subsequently, the bent SPA was photographed, and the captured image was processed using ImageJ software. The primary focus of the measurement was to determine the twisting angle, which represented the curvature along the y-axis.

To maintain measurement accuracy, precautions were taken to prevent gas leakage from the SPAs. Prior to conducting measurements, all samples underwent a thorough check by inflating them with 3-bar pressure for 30 seconds to 1 minute to ensure no signs of leakage were present. Detecting signs of leakage was straightforward, as they typically manifested as hissing sounds, unstable pressure, continuous pressure decrease, or the noticeable release of air from the SPAs. Any SPAs displaying signs of leakage were excluded from the experiment.

Each sample were tested 5 times, and the average result was used. The standard deviation of the experiments was varied between 1% to 5%. After obtaining the best model, the thumb SPA was tested in real practice with other four SPA fingers. The SPAs were attached to special glove designed for this purpose, as shown in Figure 3.

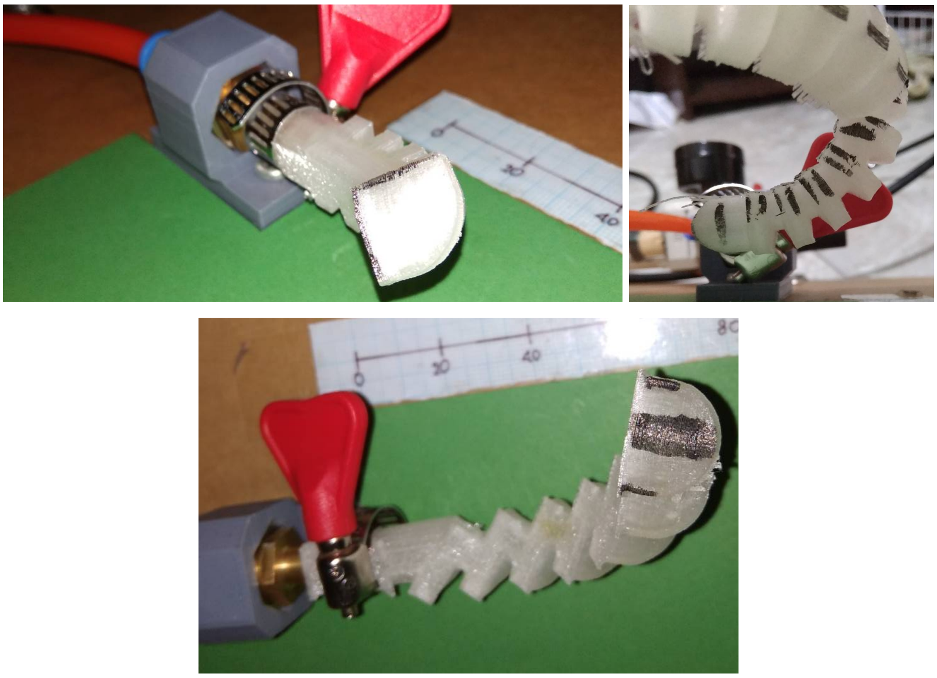

Fig. 3. The SPAs were inflated and measured.

III. Results and Discussion

As mentioned in the previous section, the thumb exhibits distinct movement patterns compared to the other four fingers due to its ability to move in two axes. In order to execute picking and grasping motions effectively, the thumb must perform a twisting motion at the Carpometacarpal (CMC) joint. Referring to Figure 1, it is essential for the twisting motion to have a minimum range of 71 degrees.

Table 2. The result of the measurement of twisting angle.

Twisting angle				
No	**Model**	**Twist 2bar**	**Twist 2,5bar**	**Twist 3bar**
1	M1	19,04	21,48	22
2	M2	4,14	5,72	9,17
3	M3	69,5	83,38	85,56

To ease the analysis, the data from Table 2, is converted into a graph in Fig 4. From the graph, all of the model had succeeded to show the twisting angle as expected. However, M3 model produces the most curvature when compared to the other two models. At a pressure of 2bar, the bending angle produced by the M3 geometry has reached 70 degrees, which was required by the task. Although the M1 model produces a large enough twist when compared to the MJ2 geometry, it is still very far smaller than M3.

From this data, it appears that the M3 model is the best for twisting the CMC joint of the thumb. This is because the bending angle is the largest compared to the other two models with the same pressure and number of chambers. Two sections of SPA worked very well and optimum, with the first section made a bending movement around y-axis, and the second section made a bending movement around x axis.

However, the M1 model actually showed a good potential to achieve large twist angles, moreover when the number of balloons is increased. This the researchers found when they increased the number of balloons in the MJ1 model to 8 balloons, the twist angle could reach 47 degrees at a pressure of 3 bar. And the angle can get bigger if the number of balloons is increased.

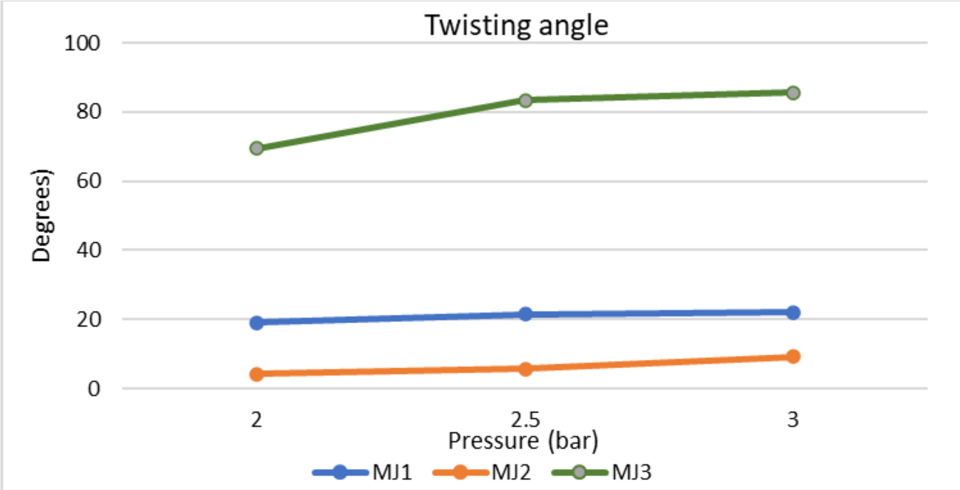

Fig. 4. The graphic of the result of twisting angle measurement

Meanwhile the M2 model is still not effective when used to get a twist angle to move the thumb. This is because the resulting torsion angle is still very small and far from the desired angle.

After obtaining the result that M3 provide the best twisting angle, this model than integrated with the other four finger shape SPAs to move the hand. The result was going well, both of grasping and picking like movement can be achieved by using M3 mode, as shown in Figure 5 and Figure 6.

Fig. 5. Applying M3 with the glove to move human hand in picking-like movement.

Fig. 6. Applying M3 with the glove to move human hand in grasping movement.

IV. Conclusion

In conclusion, this research was aimed to find the suit model of soft pneumatic actuator to move human thumb specifically for post-stroke rehabilitation glove purpose. There were three model that were tested in this experiment, they were called M1, M2, and M3. These three models were tested by inflating them using pressurized air, and the twisting angle were measured. From the result it seems that M3 show the better result. M3 was the SPA model with two sections of chambers in two different axes. M1 actually showed a good potential to achieve the task, if the number of chambers was increased. Meanwhile M2 seems not effective and just showed a small twisting angle. M3 also shown a good performance when applied along with all four SPA finger to move the hand to do grasping and picking like-movement.

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