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*Research Article*

# Soft Pneumatic Actuator Designed After Human Finger Motion

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**Abstract:**
*Soft pneumatic actuators (SPAs) are characterized by their soft, flexible, and compliant nature. Typically made from elastomeric materials, SPAs are controlled through the inflation and deflation of pneumatic chambers or channels. Their adaptability and compliance make them suitable for various applications, including deep-water exploration, wearable devices, soft robotics, and human-machine interaction. In this study, a soft pneumatic finger actuator inspired by the human finger was designed. The Ogden hyperelastic material model was used to simulate the bending behavior of the actuator. The analysis revealed that the SPA exhibited noticeable bending or deformation (19.58 mm) with higher pneumatic pressure (10 kPa). To further improve deformation or bending behavior, an air gap was introduced between adjacent chambers. This modification resulted in increased deformation (55.3 mm) of the SPA, even at lower pressures (5 kPa) compared to the original design. In the future, this design could be used for the development of soft wearable hand glove for rehabilitation exercises.*

**Keywords:** *SPA, Pneumatic, Actuator, Bending, FEA, Finger*

## 1. Introduction

In recent years, soft robotics has been recognized as a revolutionary innovation with the potential to revolutionize the current state of medical fields. These flexible and versatile technologies, which are typically inspired by the movements and behavior of live organisms, opened up new opportunities for healthcare inspection, treatment, and rehabilitation applications [1]. In comparison to rigid or traditional or conventional robots, soft robots can replicate the flexibility and softness of human tissues, making them appropriate for delicate and difficult medical operations [2, 3]. The compliance, flexibility, and adaptability of these robotic structures make them different and effective as compared to rigid robots. They are made up of soft materials that allow for a wide range of deformations, as compared to standard rigid robots. Silicone rubber, textiles, shape-memory alloys, and elastomers are some of the most frequently utilized materials [4, 5]. Nature, such as the working of tendons and muscles in the human body, is commonly used to inspire these robotic structures. They can now perform jobs with greater precision and softness, which is highly essential in medical applications. Soft robots use a range of actuation mechanisms for carrying out various activities or tasks. For example, hydraulic and pneumatic systems are commonly employed to actuate the soft body of the robot, resulting in regulated and gentle movements. Furthermore, shape memory alloys, which change shape in response to temperature changes, provide another actuation technique. Other frequently utilized techniques include electro-active polymer actuators, variable length tendons, material jamming actuators, magnetic actuators, and many others [6, 7].

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Soft robots may now examine complex structures within the human body without causing any harm. However, these robots in medical applications require advanced sensing and control systems. For example, force and touch sensors allow the robot to detect its immediate surroundings and interact safely with the patient or surgical environment. As a result of advanced control systems, these robots can perform jobs much more precisely than before and can respond to unexpected changes during medical operations [8, 9].

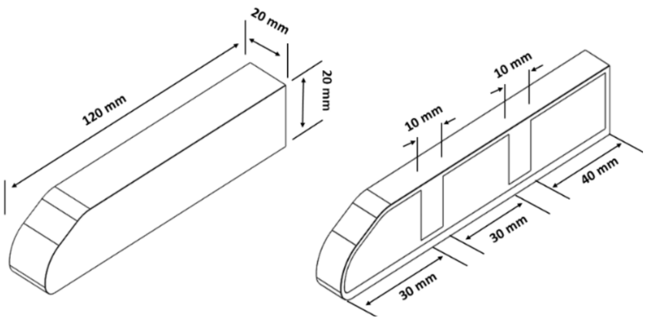
Soft robotic devices are being employed in rehabilitation and physiotherapy applications. They can be used to help those who are physically challenged. For example, soft exoskeletons can be used to help and improve the patient's gestures [10]. In addition, people with strokes typically struggle to regain control of their bodies. Thus, soft robotic devices can provide targeted therapy by assisting patients in performing repetitive and regulated activities. These devices can respond to the patients' development and so gradually improve the intensity of therapy [11]. In particular, the area of minimally invasive surgery (MIS) has benefited greatly from soft robotic devices [12]. Traditional operations usually require large cuts or wounds, which results in lengthy and painful healing processes and a higher risk of infection. However, soft robots can be inserted through small wounds and can move through complex biological structures without causing any damage. Thus reducing the suffering, trauma, and recovery time for the patient. Further, these robots have also proven to be very useful in endoscopic and gastrointestinal treatments, since they can bend, twist, and adjust to the shape of the patient's intestines, allowing for more precise examinations and treatments. They can also be integrated with cameras and sensors to diagnose and treat conditions like tumors, polyps, and gastrointestinal bleeding [13]. These robotic structures have brought a new era in the healthcare field by providing novel methods to the longstanding problems. Their unique characteristics make them great instruments for improving the diagnosis, treatment, and rehabilitation of patients.

Soft actuators provides new opportunities to develop adaptable and dexterous robotic systems, which mimics the flexibility and functionality of natural organisms. Therefore, it is essential to understand how these actuators behave under varying pneumatic pressures for maximizing their efficiency and applicability across various industries. Through numerical simulation, this study aims to determine the mechanical behavior of a SPA inspired by the human finger. This will provide valuable information that can drive advancements in robotics, prosthetics, and biomedical engineering. The SPA is assumed to be made of hyperelastic (Ecoflex-OO30) material, thus the hyperelastic material model is utilized to observe the bending of the SPA. The rest of the paper is organized in the following sections. The structural design and finite element analysis (FEA) of the SPA is presented in Section 2. Further modification in the design of the SPA is provided in Section 3. At last, the conclusion of this study is presented in Section 4.

## 2. SPA Design and FEA

### *2.1. SPA Structural Design*

The design of a soft pneumatic finger or actuator using SolidWorks software is presented in Fig. 1. The presented soft finger or SPA considered to be 120 mm in length, 20 mm in width, and 20 mm in thickness. The SPA is divided into three sections of 40 mm, 30 mm and 30 mm respectively (shown in Fig. 1b), each separated by walls of 10 mm thickness that resemble to human finger joints. The side walls of the entire SPA are 2.5 mm thick, which ensures the structural integrity. Notably, the top wall is 1.5 mm thick, which is thinner than the lower wall that is 3 mm thick. The low thickness allows expansion at the top surface, which results in a directional bend towards the lower side due to stiffness differences between the upper and lower layers.




(a) (b)

**Fig. 1.** Structural design of the SPA.

By mimicking human finger joints, the SPA or soft finger achieves a curve path during pneumatic actuation. This bending SPA is crucial for applications in various fields, such as robotics and prosthetics. However, individual section and thickness variations in the SPA or soft actuator walls allow controlled bending, which mimics the natural movement of a human finger. This innovative design approach highlights the potential of computer-aided design software in soft robotic systems with biomimetic functionalities.

*2.2. FEA*

This study utilizes finite element analysis (FEA) technique to evaluate mechanical properties of non-linear material, specifically hyperelastic material Ecoflex-OO30. The Ecoflex-OO30 is a silicone rubber that deform significantly under small loads and does not follow Hooke's law, which indicates Ecoflex-OO30 exhibits nonlinear stress-strain relationship [14, 15]. Thus requiring hyperelastic material model for the characterization of their nonlinear behavior. There are various types of hyperelastic material models, such as Neo-Hookean, Aruda Boyce, and Ogden model [16, 17], each with specific advantages and limitations. But in this study, the Ogden model is considered for simulation as it can accurately captures large volumetric strain as in case of Ecoflex-OO30 silicone rubber. Therefore, the strain energy density function of the Ogden model is essential for defining the response of the hyperelastic material and is given by [18]

$$U = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}\left(\lambda_1^{-\alpha_i} + \lambda_2^{-\alpha_i} + \lambda_3^{-\alpha_i} - 3\right) + \sum_{i=1}^{N} \frac{1}{D_i}(J_{el} - 1)^{2i} \tag{1}$$

In the strain energy density function associated with the Ogden model equation (1), the first term, governed by $\lambda$ and $\alpha_i$, represents the shear behavior of the material, while the second term, influenced by $D_i$ and $J_{el}$, represents its compressibility behavior. Given that Ecoflex-OO30 is a hyperelastic material, its compressibility is nearly negligible. Consequently, the terms involving $D_i$ and $J_{el}$ becomes negligible or zero. However, the material constants $\mu_i$ and $\alpha_i$, essential for defining shear behavior, are determined through experimental stress and strain data. For this study, the material constants are taken from the literature [19] and the value of $\mu_i$ and $\alpha_i$, are $4.807 \times 10^4$ Pa and 0.548, respectively. Additionally, $\lambda_1$, $\lambda_2$ and $\lambda_3$ denote the principal stretches along the three principal axes x, y and z, respectively. Moreover, the hyperelastic analysis of soft finger or SPA made up of Ecoflex-OO50 is conducted on Abaqus 6.14 software. The SPA model is meshed using C3D10H tetrahedral-type hybrid elements (shown in Fig. 2 a, b). A grid independence test has been conducted to confirm that the numerical results are not influenced by the discretization of the model. This ensures that a total of 642,125 nodes and 297,541 elements are sufficient for achieving accurate results without unnecessarily increasing computational cost. For boundary conditions, one side of the SPA is assumed fixed, while the opposite side is left free to deform, as provided in Figures 2 c, d. Whereas loading condition includes the application of pneumatic pressure or compressed air on the inner hollow surface of the SPA, exerting force perpendicular to the inner face, as presented in Figure 2c.

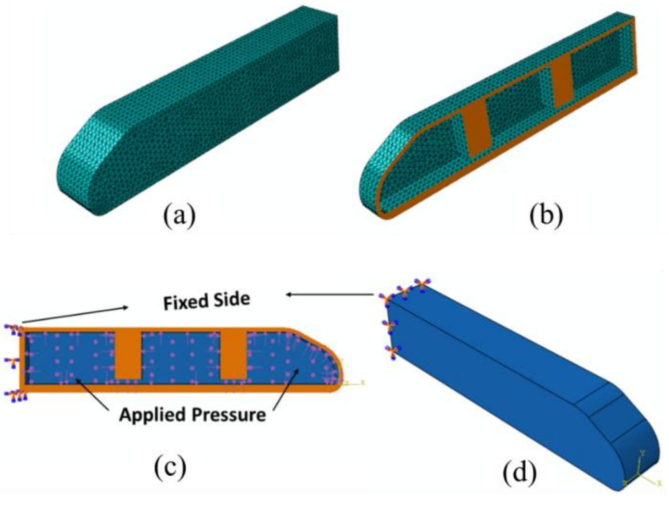



**Fig. 2.** The SPA model is meshed using C3D10H tetrahedral-type hybrid elements (a,b) mesh model and (c,d) boundary and loading conditions.

Initially, the soft finger or SPA is actuated with a pneumatic pressure of 1 kPa, which is not sufficient to produce noticeable bending in the SPA. Therefore, the SPA is actuated with an increased pneumatic pressure of 5 kPa, which led to the expansion of top surface of the SPA. This expansion led to the development of bending moment which directed towards the lower or bottom layer of the SPA. The observed bending phenomena is due to the stiffness difference between layers, which highlights the significance of material selection and structural design in optimizing the performance and efficiency of soft actuator. The bending deformation of the SPA under 5 kPa pneumatic pressure is shown in Fig. 3. The regions with blue color indicates minimal or negligible deformation, whereas red regions indicates maximal deformation.

Fig. 4 presents the stress distribution on the soft finger or SPA under an actuation pressure of 5 kPa. The applied pneumatic pressure induces inflation in the SPA, while its walls resist this pressure. This results in tension and stress, specifically in the top and side walls of the SPA. The color contour represents the corresponding stress experienced by the SPA. Notably, at 5 kPa, the maximum stress generated in the SPA reaches to 0.23 MPa, whereas experiences a maximum downward deformation of 5.58 mm.

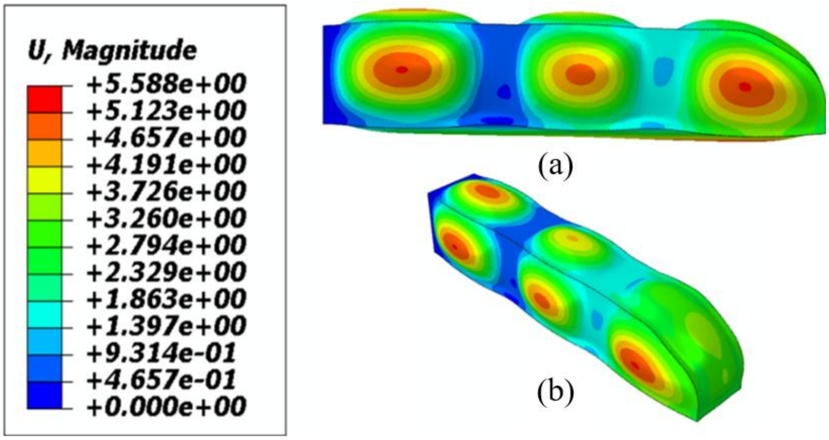



**Fig. 3.** SPA deformation at pneumatic pressure of 5 kPa.

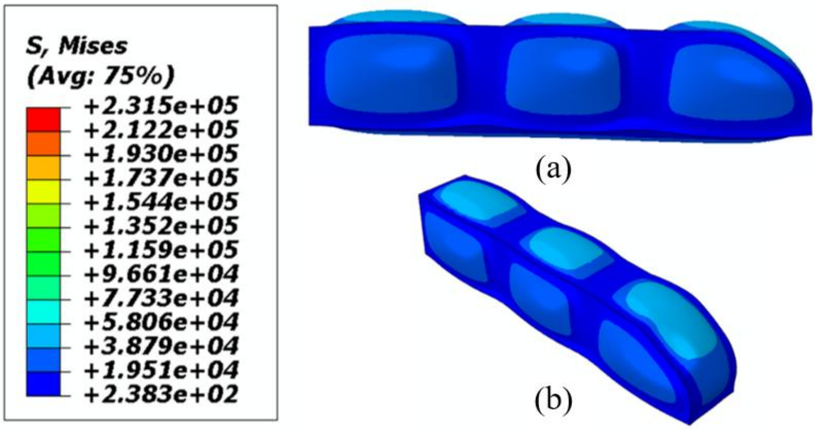



**Fig. 4.** Stress distribution at pneumatic pressure of 5 kPa.

As the pneumatic pressure increases to 10 kPa, the soft finger experiences increased mechanical stresses and deformations. The SPA shows a significant downward deformation of 19.58 mm (shown in Figure 5) and experiences a maximum stress of 0.52 MPa (shown in Figure 6). This notable increase in stress and deformation compared to the 5 kPa pressure demonstrates the enhanced bending capacity of the SPA under higher actuation pressures. However, only two pressure levels has been considered (5 and 10 kPa), which resulted in limited deformation. It is clear that increasing pressure would lead to greater bending or deformation but it has some limitations. The SPA is considered to be of Ecoflex, a silicone rubber that can be prone to puncture or bursting at higher pressures. Therefore, to ensure both safety and performance, we aim to redesign the SPA to achieve higher deformations even at low pressures, enhancing both its efficiency and reliability. Moreover, it can be observed that the 10 mm thick joint in the design is resisting the bending of the finger. Further modification in the joint, such as removing the solid joint or providing an air gap between the adjacent chambers could increase the SPA bending. Therefore, some modification in the SPA or soft finger design are required, which are presented in the following section.

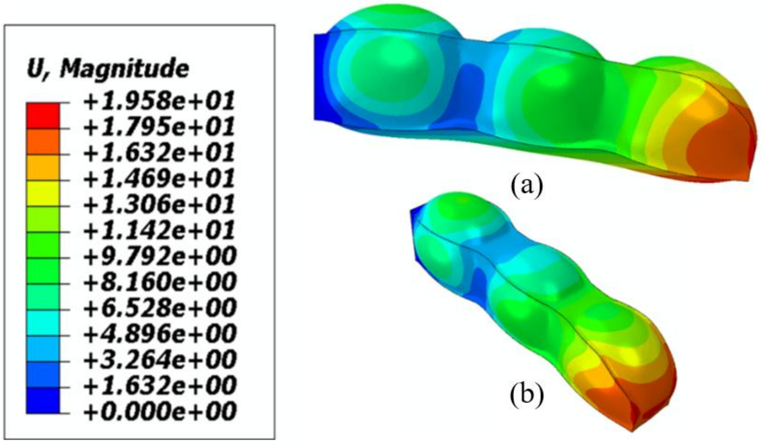



**Fig. 5.** SPA deformation at pneumatic pressure of 10 kPa.

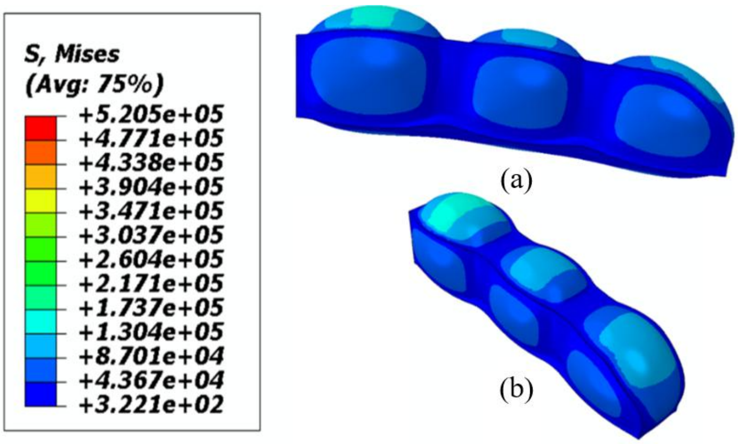



**Fig. 6.** Stress distribution at pneumatic pressure of 10 kPa.

## 3. Design Modification

To improve the bending capabilities of the soft pneumatic finger or SPA, a design modification has been carried out. Specifically, the solid connecting wall between adjacent chambers has been replaced with an air gap of 5 mm thickness (shown in Fig. 7). By applying this alteration, the design enables the air gap to expand, facilitating increased bending angles. Additionally, the side walls adjacent to the air gap maintain a thickness of 2.5 mm, which ensures the structural integrity of the SPA while accommodating the desired deformation. However, replacing the solid walls with an air gap reduces the overall stiffness of the structure. While this helps with bending, it may hinder the ability of the SPA to support heavier loads. Moreover, the modified design may experience higher material stresses, particularly in the regions around the air gap. Therefore, the thinner walls around the air gap may be more susceptible to wear and tear, especially after repeated cycles of pressurization and deflation. Over time, this could lead to micro-tears or leaks, which would reduce the efficiency of the SPA.

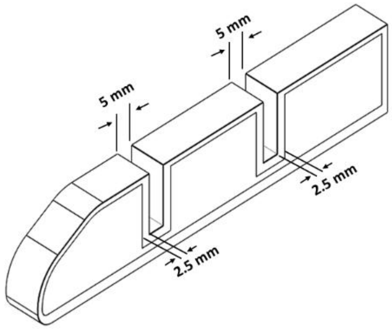



**Fig. 7.** The modified design of the soft finger or SPA.

In the modified soft pneumatic finger or SPA, initial actuation with a pneumatic pressure of 1 kPa results in significant bending that demonstrates a maximum deformation of 3.5 mm, as presented in Fig. 8. This notable increase in bending angle compared to the previous design is mainly due to the presence of an air gap between chambers, which enhances flexibility and deformation capabilities. Additionally, the SPA experiences a maximum stress of 0.01 MPa, which is shown in Fig. 9. This observation highlights the effectiveness of the design modification in enhancing the bending performance of the SPA. By introducing an air gap between chambers, the modified SPA exhibits improved flexibility that allows higher deformation under relatively low pneumatic pressures.

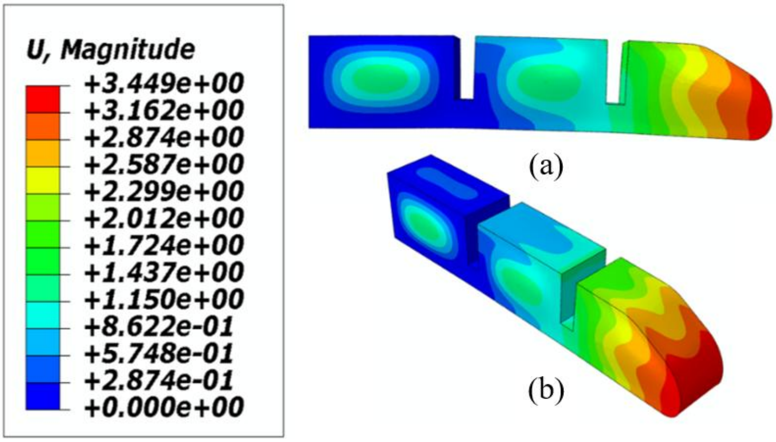



**Fig. 8.** Soft finger or SPA deformation at 1 kPa pneumatic pressure.

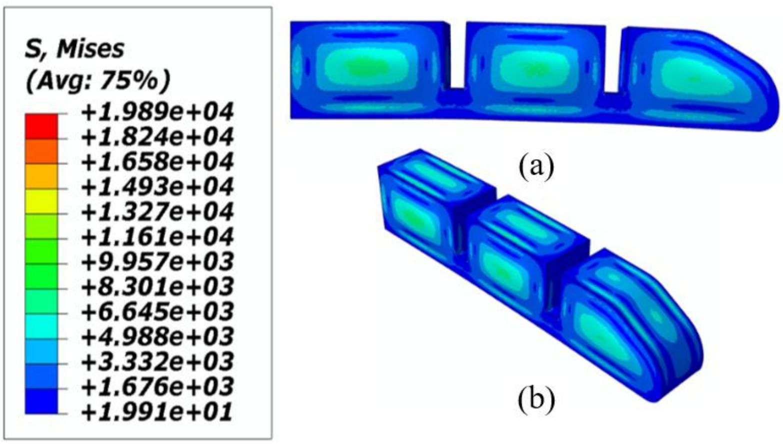



**Fig. 9.** Stress distribution in the soft finger or SPA at 1 kPa pneumatic pressure.

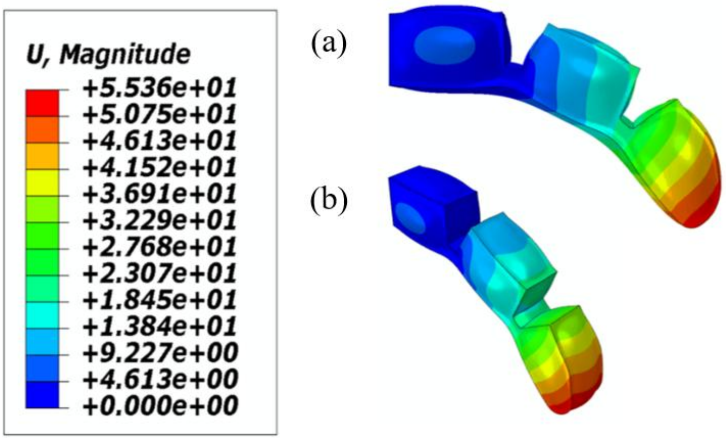



**Fig. 10.** Soft finger or SPA deformation at 5 kPa pneumatic pressure.

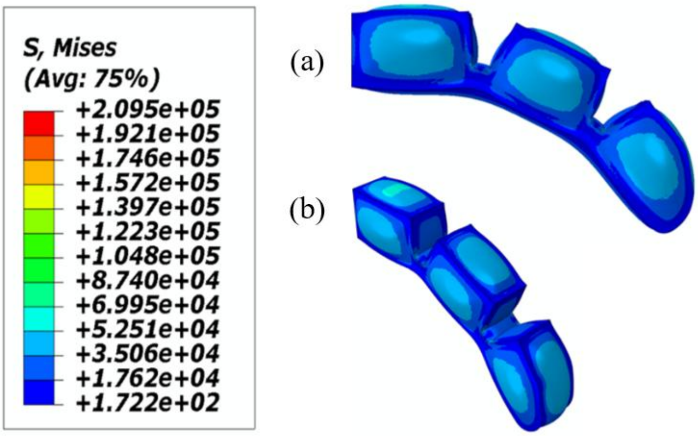



**Fig.11.** Stress distribution in the soft finger or SPA at 5 kPa pneumatic pressure.

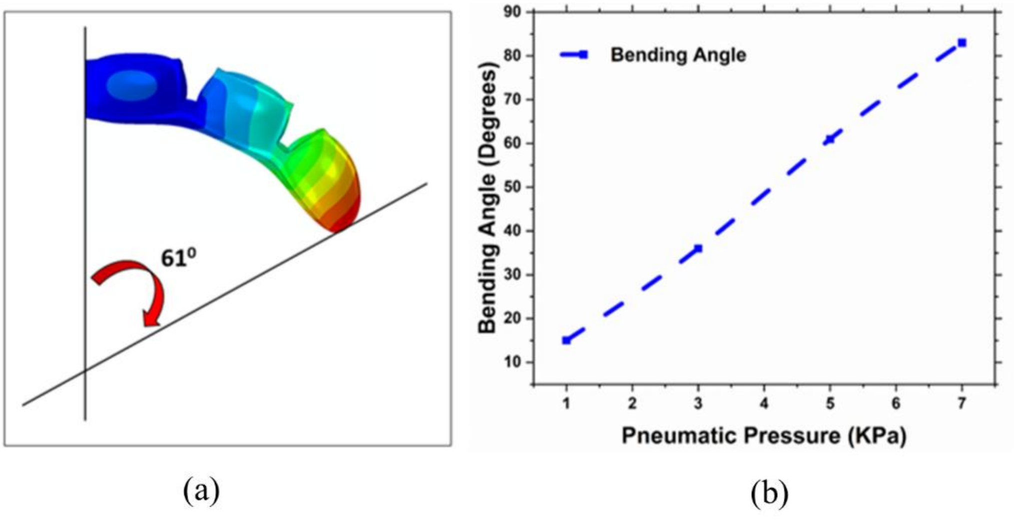



**Fig. 12.** (a) SPA bending measurement configuration and (b) modified SPA bending at different pneumatic pressures.

By increasing the actuating pneumatic pressure from 1 kPa to 5 kPa, the modified SPA exhibits a noticeable increase in bending, as presented in Fig. 10. This enhanced bending capability surpasses that of the earlier SPA design under the same pneumatic pressure. Moreover, the modified SPA generates higher bending at 5 kPa pneumatic pressure compared to the bending observed in the earlier SPA design at 10 kPa, which indicates the superior performance of modified SPA. Additionally, the SPA experiences a maximum stress of 0.21 MPa (shown in Fig. 11), which is lower than the stress observed in the earlier SPA design under the same pneumatic pressure. These results suggest that the modified soft finger or SPA design effectively enhances bending capabilities while reducing stress values, which improves the mechanical performance of the SPA. Further analysis involves actuating the modified SPA design with pneumatic pressures ranging from 1 kPa to 7 kPa at intervals of 2 kPa, as shown in Fig. 12. This simulation aims to evaluate the relationship between actuating pneumatic pressure and bending behavior, which provides valuable information for optimizing the design and functionality of soft finger or SPA in various applications.

## 4. Conclusion

This study focuses on modeling and analysis of a soft pneumatic finger or soft pneumatic actuator (SPA), getting motivated from the mechanics of the human finger. Further, utilizing a hyperelastic material (Ogden) model, the study explores the SPA's response to varying pneumatic pressures. The results of the simulation indicates that higher pressures led to increased deformation and stress levels, which defines a proportional relationship between pressure and mechanical responses. However, soft finger or SPA design is modified in order to enhance the bending response. Thus, an air gap is introduced between the adjacent chambers in place of solid connecting wall. This design modification results in the enhanced bending capabilities. Notably, the modified SPA starts bending at a significantly lower pneumatic pressure of 1 kPa compared to the earlier design, which required 5 kPa for similar behavior. Moreover, the modified SPA design achieves higher bending angle at 5 kPa than the earlier SPA design obtained at 10 kPa. The findings of this study suggest that the modeled SPA effectively mimics the functionality of human finger. Therefore, these SPAs could be utilized for the development of soft wearable gloves for rehabilitation exercises. Moreover, key geometrical parameters (including chamber size, wall thickness, and air gap) have been considered in this work. However, mathematical bending model to validate the bending results and additional geometrical factors, such as tapering and segmenting, will be explored in the future to further enhance the performance and flexibility of the actuator.

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