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Research paper

Computational Modeling and Finite Element Analysis of Bio-Inspired Soft Pneumatic Actuators for Robotic Straightening

Mohammad Suhaimi Selomah [1] *, Noorhamizah Mohamed Nasir [1]*, Jamaludin Jalani [1], Hisyam Abdul Rahman [1], Kim Gaik Tay [1], Danial Md Noor [1], Mohd Shamian Zainal [2], Saif Huq [3]

[1] *Department of Electronic Engineering, Faculty of Electrical and Electronic Engineering,86400 Parit Raja, Batu Pahat, Johor, Malaysia*
[2] *Department of Electrical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Higher Education Hub, 84600 Pagoh, Muar, Johor.*
[3] *Department of Electrical and Computer Engineering, and Computer Science, Kinsley School of Engineering, Sciences and Technology, York College of Pennsylvania, York, PA, USA*
**Corresponding author E-mail: hamizahn@uthm.edu.my*

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Abstract

This study presents the design and analysis of a bioinspired soft pneumatic actuator (BSPA), using the finite element method (FEM), to simulate the opening and closing movements of the human hand. The primary objective was to explore its potential application in assisting stroke survivors during rehabilitation, specifically targeting the treatment of spastic-clenched fist deformities. Drawing inspiration from the biomechanical motion and anatomical structure of the human hand, the actuator was engineered to actively extend while passively flexing, mimicking natural hand movements. Key design parameters, including actuator width (16 mm), wall thickness (2 mm), actuation angles, and chamber dimensions, were fine-tuned through iterative simulation to optimize the actuator's mechanical response. The design process was conducted using SolidWorks, with subsequent performance evaluation and simulation conducted in Abaqus CAE. Finite element analysis allowed for a detailed examination of the actuator's behavior under different loading conditions, ensuring accurate predictions of its functionality. Simulation results indicated that the BSPA could extend to a 90° angle at a pressure of 110 kPa, demonstrating the potential to mimic full hand extension. Additionally, block force tests showed that the actuator generated a total force reaction of 3N at 80 kPa, a level of force sufficient to fully open the hand when integrated into a soft robotic glove. This force output was carefully evaluated to ensure it pro-vided sufficient assistance for stroke survivors experiencing muscle spasticity, without compromising safety or comfort. These findings provide critical insights into the development of soft pneumatic actuators (SPAs) for medical and rehabilitative use, particularly for assisting patients with hand mobility impairments. The study highlights the effectiveness of bioinspired designs in creating soft actuators that can reproduce complex biomechanical movements. The results pave the way for further refinement and application of BSPAs in soft robotic gloves for rehabilitation, offering a promising solution for improving the quality of life for stroke survivors by enhancing hand functionality and motor recovery.

Keywords: *Bioinspired Soft Pneumatic Actuator (BSPA); Finite Element Method (FEM); Stroke Rehabilitation; Soft Robotics, Hand Mobility.*

1. Introduction

Soft Pneumatic Actuators (SPAs) have gained much attention in soft robotics because of their intrinsically compliant nature and versatility, which allows safe interaction with humans [1]. Such actuators are promising in bioinspired design for rehabilitation and assistive devices, especially those that are hand-controlled [2]. A stroke happens when a clot blocks or ruptures an artery responsible for transporting oxygen and essential nutrients to the brain. When it happens, certain areas of the brain die because they lose their supply of blood and oxygen [3], [4]. As one of the leading causes of disability worldwide, stroke often results in motor impairments such as spastic clenched fist deformity, where increased muscle tone causes the hand to remain in a clenched position, severely limiting its functional use [5]. Hand function improvement and spasticity reduction are often achieved using repetitive motion exercises in rehabilitation procedures [6], [7]. A structured rehabilitation method is proposed, involving initial patient assessment, customization of the SPA device, repetitive motion exercises, brain-wave-controlled feedback [8], continuous muscle activation monitoring [9], [10], strength and functional training, and long-term use, including home-based rehabilitation.

SPAs as documented in existing literature, typically exhibit two defining features: they are made from flexible materials containing internal air chambers or pneumatic networks, and they rely on air pressure to execute various compliant motions, including contraction, elongation, bending, curling, and torsion. However, sustaining these deformations necessitates a constant supply of air pressure, which can lead to strain-induced fatigue and a shortened operational lifespan. To address these limitations, this study introduces an innovative SPA design that maintains its deformed shape during inactive phases and extends upon inflation. This advancement seeks to enhance the longevity and efficiency of the actuator, which is particularly advantageous for rehabilitation applications where long-term reliability is essential.

Previous research underscores the significance of geometric configuration and material properties in SPA design [11], [12]. Li et al. [2] highlighted design and control aspects of soft robots, emphasizing compliant materials and bioinspired designs. Polygerinos et al. [13] explored modelling fibre-reinforced bending actuators, stressing material composition and structural design in achieving desired motion capabilities. Bioinspired designs, particularly those mimicking human hand movements, have been instrumental in advancing SPA technology [2]. Li et al. discussed bioinspiration's role in enhancing robotic flexibility and adaptability, enabling actuators to replicate intricate human motions effectively.

Finite element analysis (FEA) has proven instrumental in SPA [14], predicting and optimizing actuator behaviour under diverse conditions without extensive physical prototyping. Marchese et al. outlined strategies for designing soft fluidic elastomer robots, demonstrating FEA's utility in refining mechanical performance. Wang et al. [15] analysed soft rubber actuators with fluid channels, highlighting FEA's role in optimizing actuator performance.

This study aims to contribute to the field by providing insights into SPA design optimization using FEM, particularly focusing on straightening motions beneficial for stroke rehabilitation. By exploring diverse design parameters, the research seeks to enhance SPA performance, durability, and application in rehabilitation contexts.

2. Rehabilitation Technology

Recently, we experienced a significant shift in rehabilitation technology toward soft robotics due to their interaction with humans. We observe that compared to the earlier stiff exoskeletons, soft actuators from flexible materials offer an improved experience, greater flexibility, and safety in human-robot interaction very much true in the case of neurorehabilitation. Moreover, several reports have emphasized the benefits of soft robotic gloves over rigid robotic systems. For instance, Hu et al. (2020) reported a soft robotic glove using positive-negative pneumatic action, which is that it provides assistive as well as resistive input to hand motion, thus, by this two-way control, improving rehab results [16]. Also, Boka et al. (2023) published on KNTU-RoboGlove, a pneumatic glove and soft actuator modular design that, in turn, improves the customized fit and comfort for users with diverse hand structures [18].

If we compare various studies that review hard exoskeletons and soft robots, we observe that although hard systems work more optimally in the context of force production, they also compromise on user comfort and have a higher chance of causing misalignment and injury. On the other hand, soft actuators are capable of generating lower forces but are superior in the long-term therapy aspect because they are compliant and thus better able to accommodate complex human movements. Also, outside soft gloves, we have recently seen in the design of soft actuators a trend towards segmented, fiber-reinforced, and hybrid structures that more directly address the range of motion and force output. For example, Kokubu et al. in 2024 demonstrated fiber-reinforced modular actuators that were more effective in boosting force output with the preservation of flexibility, which is a great proof point for reinforcing soft material integration in rehab gloves [19]. Also, Do et al. in 2021 reported a soft robotic glove that they had developed with segmented PneuNets that outperformed in accurate actuation and also mimicked natural finger joint motion [20].

From a research viewpoint, we are now located is that in the field of FEA we have reported profound progress in formulating FEM approaches, hence benefiting the design of soft actuators more efficiently with lesser use of actual prototypes. Lai et al. (2023) utilized extremely detailed FEA models to design a bidirectional soft glove that is also able to provide active and passive support [17]. Similarly, in Wang et al. (2019) came up with and showcased segmented Pneu-Nets bending actuators that they simulated and verified via FEA to study force and bending characteristics [21]. These reports hypothesize that from early on in the design process, the use of FEA is to be integrated as a tool that also allows the designer to have a comprehensive set of geometric configurations, material characteristics, and actuation patterns under consideration.

Overall, we observe that where bioinspired design, soft material engineering, and advanced simulation methods meet, soft robotic actuators are at a very promising place in rehab, such as stroke care. Here, we present an actuator in line with the direction of recent research as a highly tunable design, which we have modeled using Finite Element Modeling for angular displacement as well as for output force, thereby bridging the gap between what we see in terms of flexibility and function in existing designs.

3. Method

3.1. Design of Bioinspired Soft Pneumatic Actuator (BSPA)

Many researchers draw inspiration from biological models of various creatures to achieve specific design goals, a trend that is particularly evident in the development of soft robotic hands, grippers, and actuators. As illustrated in Figure 1, the human finger is composed of linked phalanges connected by three key joints: the metacarpophalangeal joint (MCP), the proximal interphalangeal joint (PIP), and the distal interphalangeal joint (DIP). The figure shows the finger in both open (B) and closed (A) hand positions.

The BSPA proposed in this study is modeled after the human finger and its fully closed position, allowing it to safely and reliably interact with and adapt to the finger's trajectory profiles. Key functional components of the actuator, such as the initial shape, silicone body, inner chamber, and strain-limiting layer, are designed to emulate various anatomical features of the human finger, integrating these elements into the overall actuator design.

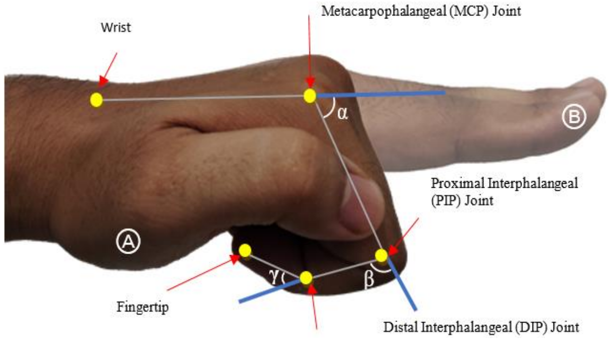

Fig. 1: Comparison of Hand Positions. (A) Closed Hand Position Showing the Finger Flexed at the MCP, PIP, And DIP Joints. The Angles Α, Β, and Γ Represent the Degrees of Flexion at Each Joint, Which Are Critical for Understanding the Range of Motion and for Designing Bioinspired Actuators That Mimic These Natural Movements. (B) Open Hand Position with the Finger Extended, Highlighting the Alignment of the Phalanges.

3.1.1. Design Requirements

Firstly, the concept of a soft actuator based on the term "active extension" describes a method that allows a soft actuator to actively extend the fingers. Next, the soft actuator's technical specification should have the same range of motion (ROM) as standard rehabilitation treatment for a clenched fist deformity. This design needs consideration for finger joint motions; according to this paper [16], we use the middle finger's bending angles as an initial guideline for a normal range of motion (NROM), as shown in Table 1.

Table 1: The NORM of Middle Joint [16]

Location	NROM (°)	Design ROM (°)
MCP	0-100	90
PIP	0-105	85
DIP	0-85	40

To make sure the actuator fits well on a closed hand, its length should match the length of each finger. This helps it stay in place and work properly. The actuator width should also be narrower than the finger to allow natural movement and fit different finger sizes. This way, it won't get in the way when the finger bends or straightens. Table 2 shows the specific dimensions of the hand, based on the average hand sizes of Malaysian Malay males [17]. These measurements help ensure the actuators fit well. If someone's finger size is different from the average, adjustments might be needed for the best fit and comfort.

Table 2: Dimensions of Hand [17]

Dimension	length (mm)
hand length	186
Middle finger length	79
hand breadth	83.3
Index finger breadth	15.8

3.1.2. Actuator Design

The design of soft actuators for human interaction often requires careful consideration of the actuator's initial shape and how it fits with the intended application. The design of BSPA is specifically tailored to fit within a closed hand in its initial state. As part of the proof-of-concept design, SolidWorks was employed, and the actuator was fabricated with a single chamber. Additionally, a strain-limiting layer was strategically positioned on the top side, specifically tailored for the middle finger. This strategic placement of the strain-limiting layer allows controlled extension motion upon the application of air pressure. Without any applied pressure, the actuator retains a specific curved shape that conforms to the hand's natural posture, as depicted in Figure 2(a). The half-round shape of the BSPA (see Figure 2(b)) draws inspiration from the work of Panagiotis Polygerinos and his team, specifically their research on soft robotic gloves. Polygerinos et al. [18] showed in their research that a half-round cross-sectional design strikes the best balance between flexibility and structural integrity compared to a round or rectangular shape.

The actuator's design was detailed, with segment lengths of 50 mm, 60 mm, 30 mm, and 20 mm, corresponding to the finger's phalanges and joints. The kinematic configuration included joint angles of 90 degrees at the MCP joint, 85 degrees at the PIP joint, and 140 degrees at the DIP joint, closely mimicking natural finger movement. In addition to these fixed parameters, key variable parameters are shown in Figure 2(b), including the width (w) and height (h) of the half-round cross-section, as well as the width and height of the chamber, which are determined by the chamber wall thickness (t1) and the upper layer thickness (t2). The height of a half-round cross-section is directly dependent on its width. Specifically, the height of the half-round is equal to half of its width. These variables play a crucial role in fine-tuning the actuator's performance, ensuring that it delivers precise and controlled movements upon pressurization. The concept 3D rendering of the actuator's structure is shown in Figure 2(c), providing a comprehensive view of its design and intended functionality.

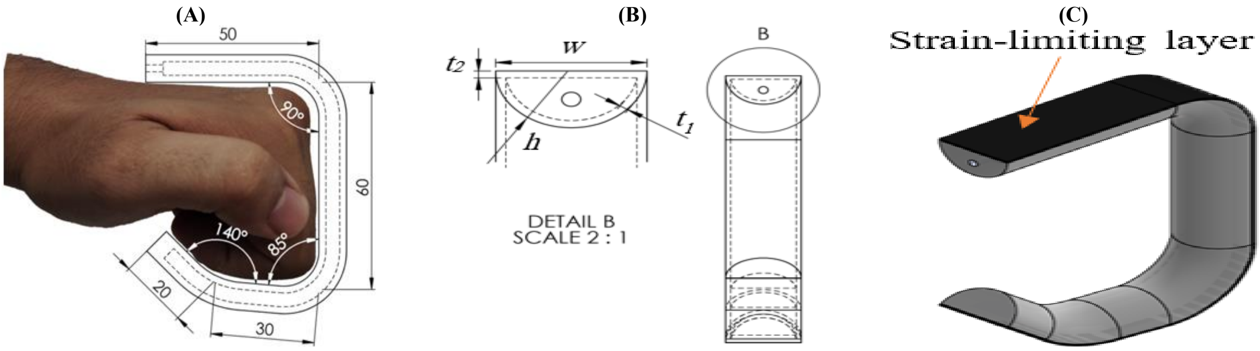

Fig. 2: Design and Dimensions of the Bio-Inspired Straightening Soft Pneumatic Actuator, (A) the Actuator Is Shaped to Fit A Closed Hand in Its Initial State, with Segment Lengths of 50 Mm, 60 Mm, 30 Mm, and 20 Mm, and Joint Angles of 90° at the MCP, 85° at the PIP, and 140° at the DIP, (B) Detailed Sectional View Showing Width, Height, and Thickness of Wall and Top Side of the Actuator. (C) A 3D Rendering of the Actuator Illustration, Showing the Positioning of the Strain-Limiting Layer at the Top Side of the Actuator

3.2. Selection of Material

The decision to use silicone rubber as the actuator material was influenced by factors such as its affordability, ease of moulding into various shapes, and desirable properties for actuation. When selecting materials, it's essential to consider stiffness, which affects the straightening angle and blocking force needed for hand-opening tasks. Additionally, one should be mindful of the risk of pneumatic passages bursting. In the material selection process for this study, Ecoflex 00-50 was chosen due to its well-documented use in soft robotics for its exceptional flexibility and low modulus of elasticity, which is ideal for creating actuators that require significant deformation under low pressure. This silicone elastomer offers a balance between softness and durability, making it suitable for replicating the complex, non-linear movements typical in soft robotic actuators. Note that the incorporation of pneumatic networks and other structural elements can cause the actual modulus of elasticity in the finished actuator to vary from the base material, even though Ecoflex 00-50 provides the necessary compliance. This variability underscores the importance of accurately modelling and simulating the actuator's performance to account for these composite effects.

3.3. Actuator Modelling

Previous research has successfully developed soft actuator models to predict their bending behaviour, closely matching experimental results [13]. These predictive models play a crucial role in optimising designs before fabrication, enabling accurate performance simulations and reducing the need for expensive prototyping. Building upon this foundation, the current study focuses on creating a detailed FEM for a BSPA. The primary objective is to analyse the actuator's behaviour and establish correlations between input pressure, resulting angular displacement, and output force. The study aims to extend the predictive modelling approach to straightening motions by exploring these relationships across various geometric parameters, ensuring the optimization of designs before physical prototyping.

3.3.1. Finite Element Method (FEM) Simulation Using Abaqus

In this paper, to gain insight into the kinematic behaviour of the soft pneumatic actuator, a single chamber of the actuator was pressurized. Such a methodology enabled the targeted investigation on how the design parameters would affect the extension motion of the actuator and the force generation. The actuator design, originally developed in SolidWorks, was imported into Abaqus as a STEP file. The used Ecoflex 0050 silicone in the finite element simulation followed the material parameters as taken from [19]. The material was modelled with the hyperelastic Yeoh model in Abaqus, considering the nonlinear elastic behaviour characteristic of soft materials. Besides the Ecoflex 0050, a thin paper layer was applied as a strain-limiting element at the top of the actuator. The paper was used to restrict extension on the top side of the actuator, thereby causing it to straighten. The material properties used in the analysis are summarized in Table 3.

Table 3: Properties of Materials

Ecoflex 0050 [19]	Paper [20]
Yeoh strain energy potential defines by the coefficient $C_{10} = 1.9 \times 10^{-2}$, $C_{20} = 9 \times 10^{-4}$, $C_{30} = -4.75 \times 10^{-6}$	Young Modulus of 6.5 GPa and Poisson's ratio of 0.2
Density of 1070 kg/m^3	Density of 750 kg/m^3

3.3.1.1. Simulation of Extension Motion

The FEM analysis was carried out by gradually increasing the internal pressure from 0 to 250 kPa to evaluate the actuator's full extension and the resulting angular displacement, targeting a tip extension motion of 90°. Figure 3 shows the BSPA transitioning from its initial position to full extension during the Abaqus simulation. The angular displacement θ indicates the extent of bending achieved at full inflation. This visual representation illustrates the deformation behaviour modelled in the FEM analysis, highlighting the impact of the strain-limiting layer and top layer, and material properties on the actuator's performance.

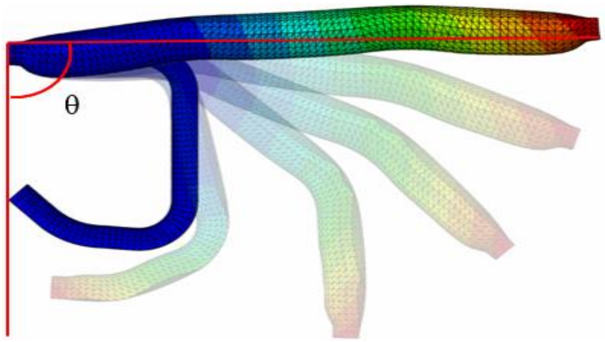

Fig. 3: BSPA from the Initial Position to Full Extension Motion in Abaqus Simulation.

3.3.1.2. Block Force Test

In addition to the extension motion simulation, a block force test was conducted using Abaqus to evaluate the actuator's force generation capabilities under constrained conditions. The block force test is a critical analysis that simulates the actuator's interaction with a rigid object, such as a block, to measure the force it can exert when its movement is restricted.

For this test, a block was placed at the tip and PIP joint of the actuator, and internal pressure was incrementally applied. The block was modelled as a rigid body with significantly higher stiffness than the actuator to ensure it remained undeformed during the simulation. Surface-to-surface contact with friction was defined to accurately simulate the interaction between the actuator and the block.

Figure 4 illustrates the results of the block force test, showing the actuator pressing against the block with a corresponding stress distribution across the actuator's body. The colour gradient in the image indicates the stress levels, with higher stresses observed near the contact area with the block and the fixed base of the actuator. The color gradient represents Von Mises stress levels, where red indicates areas of highest stress concentration and blue indicates minimal stress zones.

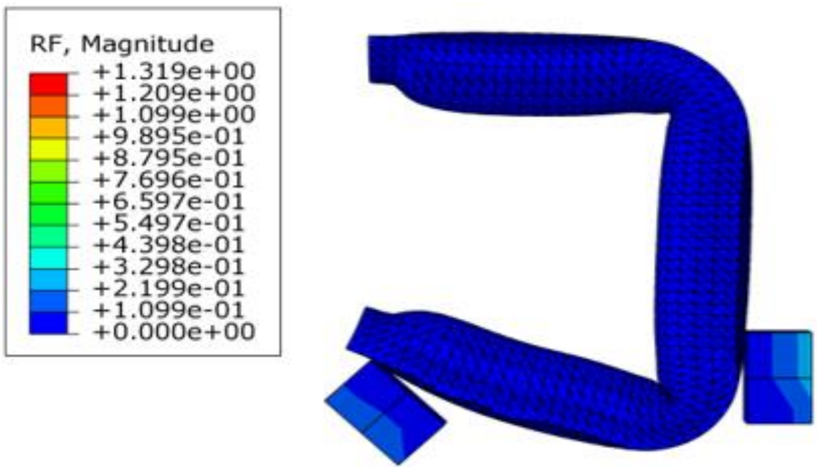

Fig. 4: Block Force Test Simulation.

The model illustrates the reaction force distribution in a bioinspired soft pneumatic actuator during a block force test. The test involved the actuator pressing against a rigid block, with the colour gradient representing the varying levels of reaction force. Higher forces are observed near the contact area with the block, demonstrating the actuator's ability to exert force when its movement is restricted by an external object.

The block force test results provide critical insights into the actuator's performance in constrained scenarios, emphasizing the importance of understanding how the actuator interacts with external objects. These insights are essential for optimizing the actuator design to meet specific application requirements.

By combining the extension motion analysis and the block force test, this FEM simulation offers a comprehensive understanding of the actuator's mechanical performance, enabling more informed design decisions that enhance both flexibility and force generation capabilities.

3.3.1.3. Parameter Optimization

The total length of the actuator is not the key parameter because it is kept constant at L = 160 mm. Optimized key parameters are displayed in Figure 2(b), including the width of the actuator, the thickness wall chamber, thickness of the Top layer. Specific variable selections are listed as follows.

1) Width of actuator w: 14 mm, 15 mm, 16 mm.
2) Thickness of chamber t1: 1 mm, 2 mm, 3 mm.
3) Thickness of Top Layer t2: 1 mm, 2 mm, 3 mm.

4. Result and Discussion

In this section, we present the findings of simulation analysis carried out on the BSPA, focusing mainly on three crucial parameters: actuator width, wall thickness, and top layer thickness. The effect of each parameter on the angle of extension motion and the forces developed at different pressure conditions is systematically established.

4.1. Effect of Actuator Width

The width is one of the primary parameters that define the actuator's geometry. The width is directly related to how it affects the mechanical behaviour in terms of angular displacement and force. The analysis was performed using different applied pressures for three different widths: 14 mm, 15 mm, and 16 mm.

As illustrated in Figure 5, the angular displacement increases with the applied pressure for all the BSPA widths. The 16 mm actuator obtained the highest angular displacement of 92° at a pressure of 47 kPa compared with the 15 mm and 14 mm actuators, which obtained 86° and 79°, respectively. These simulation images are consistent with such results, showing much larger curvatures obtained by the 16 mm actuator. These results suggest that actuators with larger widths would be more flexible and hence capable of larger angular displacements.

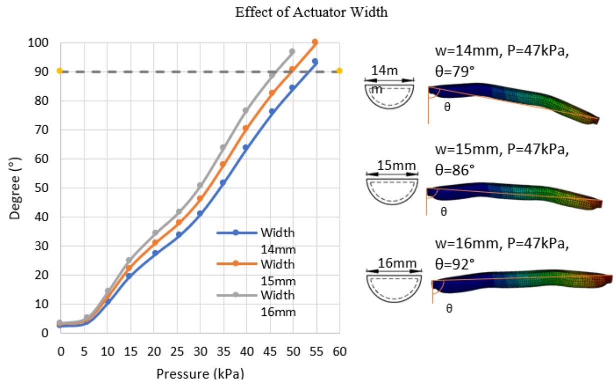

Fig. 5: The Plots Here Show the Angular Displacement as a Function of Pressure for Three Different Cases: BSPA with Widths of 14 Mm, 15 Mm, and 16 Mm. the Simulation Images on the Right Show Actuator Shapes at 47 Kpa, with the 16 Mm Actuator Obtaining the Largest Angle of 92°, Followed by 15 Mm at 86° and 14 Mm at 79°.

Figure 6 shows the force vs. pressure relationship for the three actuator widths. The results indicated that the output force rises linearly with pressure for all the widths, with the 16 mm actuator producing the highest force, reaching about 1.5 N at 40 kPa, followed by the 15 mm actuator at 1.2 N and the 14 mm actuator at 1.0 N. As the width increases, so does the surface area, which enhances the ability to generate force. These findings underscore that actuator width is a critical design parameter for applications requiring both high force and significant angular displacements.

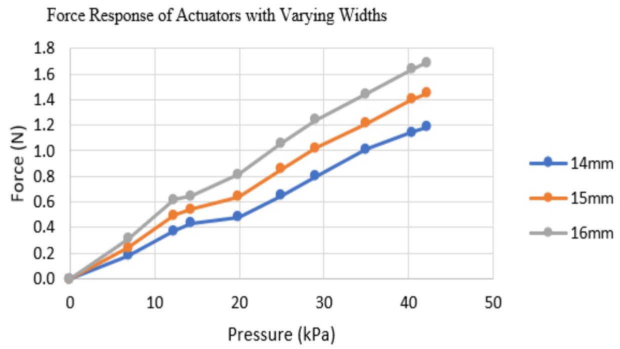

Fig. 6: Force Generated by BSPA of Widths 14 Mm, 15 Mm, and 16 Mm at Increased Applied Pressure. The graph shows that the 16 mm Actuator Can Produce a Higher Force at All Levels of Increased Applied Pressure Compared to the 15 Mm and 14 Mm Actuators.

4.2. Effect of Wall Thickness

Wall thickness is another critical parameter that determines structural integrity and performance in soft actuators. The effect of 1 mm, 2 mm, and 3 mm wall thickness actuators on angular displacement and force generation was analysed.

From Figure 7, it is visible that the angular displacement reduces with increasing wall thickness. The 1 mm thick actuator reaches the highest angle, which is 94° at 48 kPa; the 2 mm and 3 mm actuators reach 30° and 9° at the same pressure, respectively. The simulation images further explain that the increased thickness of the walls proportionally relates to decreased flexibility and increased stiffness. This suggests that applications requiring higher angular displacement can benefit from thinner walls because they are more flexible and tend to bend more easily under applied pressure.

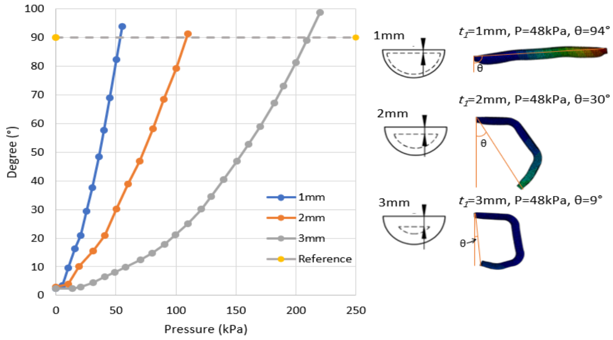

Fig. 7: Angular Displacement as a Function of Pressure for BSPA with Wall Thicknesses of 1 mm, 2 Mm, and 3 mm. The simulation Images on the Right Show the Actuators' Deformation at 48 kPa, with the 1 Mm Actuator Extended to 94°, the 2 Mm to 30°, and the 3 Mm to 9°.

Figure 8 shows the force generated by the actuators as a function of pressure. The 2 mm actuator generates the highest force at moderate pressures, reaching a peak of 3.0 N at 80 kPa, while the 3 mm actuator demonstrates a significant increase in force at higher pressures, surpassing the other two actuators beyond 140 kPa. These results suggest that while thinner walls are more flexible, thicker walls are better suited for applications requiring high force generation, particularly at higher pressures.

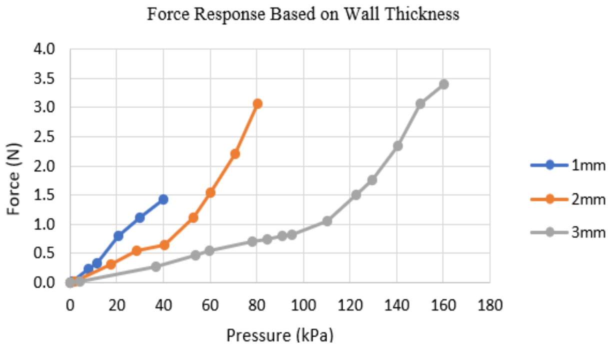

Fig. 8: Force Generated by BSPA with Wall Thicknesses Of 1 Mm, 2 Mm, And 3 Mm as A Function of Applied Pressure. The Graph Highlights That the 2 Mm Actuator Generates the Highest Force at Moderate Pressures, While the 3 Mm Actuator Shows A Significant Increase at Higher Pressures.

4.3. Effect of Top Layer Thickness

The thickness of the top layer is one of the important parameters that influences the flexibility and mechanical performance of the device. For three sets of actuators, which had a thickness of 1, 2, and 3 mm of the top layer, an analysis was made on the influence it had on the angle during the extension motion and the force applied

Figure 9 shows the plot of angular displacement versus pressure for different top-layer thicknesses. The maximum value achieved for the actuator with a 1 mm top layer is 94° at 48 kPa. For 2 mm and 3 mm, the peak bending angles are 74° and 54°, respectively. Simulation images confirm that as the thickness of the top layer increases, the actuator becomes less flexible and therefore does not offer a large angular displacement. In other words, a thinner top layer is preferable for applications where significant extension motion is required.

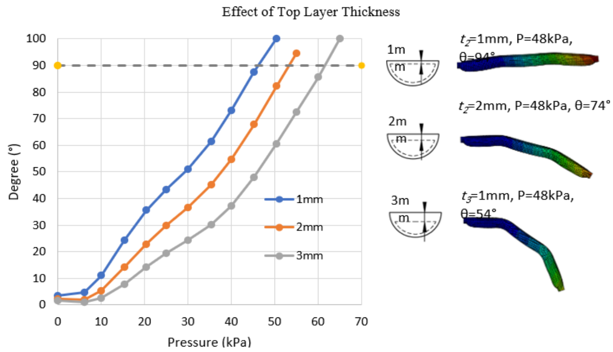

Fig. 9: Angular Displacement as A Function of Pressure BSPA with Top Layer Thicknesses of 1 Mm, 2 Mm, and 3 Mm. the Simulation Images on the Right Depict the Actuator Shapes at 48 Kpa, with the 1 Mm Top Layer Achieving the Highest Bending Angle of 94°, Followed by the 2 Mm at 74° and the 3 Mm at 54°.

From Figure 10, the force developed by the actuators remains almost constant across different top layer thicknesses and does not vary much with increasing pressure either. The increase in force output shows a linear dependence on pressure, regardless of whether the top layer thickness is 1 mm, 2 mm, or 3 mm. This indicates that the thickness of the top layer does not significantly impact force generation, suggesting that other design parameters have a greater influence on the actuators' ability to generate force.

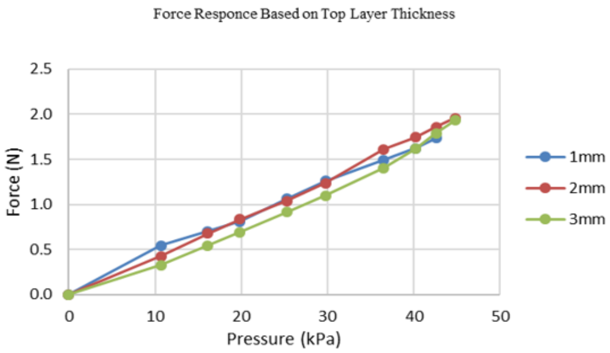

Fig. 10: Force Generated by Bioinspired Soft Actuators with Top Layer Thicknesses of 1 Mm, 2 Mm, and 3 Mm as a Function of Applied Pressure. The graph Indicates That Force Output Is Relatively Consistent Across all top-layer thicknesses, with Only Slight Variations Observed as Pressure Increases.

5. Discussion

The optimization of critical design parameters, such as actuator width (16 mm), wall thickness (2 mm), actuation angles, and chamber dimensions, played a pivotal role in enhancing the performance of the BSPA. Through detailed finite element simulations, these parameters were fine-tuned to strike a balance between flexibility and strength, allowing the actuator to achieve efficient motion. The actuator width and wall thickness were particularly influential in determining the structural integrity and responsiveness of the actuator under varying pressures. A thicker wall would have increased durability but compromised flexibility, whereas a thinner wall could lead to potential material failure. The selected dimensions provided an optimal configuration, enabling controlled deformation while maintaining structural integrity. Additionally, chamber geometry and actuation angles were designed to maximize the actuator's ability to mimic the natural motion of the human hand. This optimization process underscores the importance of precise dimensional control in soft pneumatic actuators, where small variations can significantly affect performance outcomes.

The simulations further revealed that the actuator could achieve a 90° extension at an actuation pressure of 110 kPa, demonstrating its ability to produce substantial deformation with moderate input pressure. This degree of extension is crucial for applications in soft robotic gloves, particularly in stroke rehabilitation, where the actuator must be capable of facilitating full hand extension. The achievement of a 90° bend indicates that the actuator can cover a wide range of motion, providing the necessary flexibility to assist in hand-opening movements. This finding highlights the effectiveness of bioinspired designs in reproducing complex biomechanical motions using soft, compliant materials. The moderate pressure requirement (110 kPa) also suggests that the actuator operates efficiently within safe pressure limits, making it suitable for integration into wearable rehabilitation devices without risking mechanical failure or discomfort to the user.

In addition to achieving significant angular extension, the block force tests revealed a total reaction force of 3N at 80 kPa. This force output is critical for the intended application in soft robotic gloves for stroke survivors, as it is sufficient to fully open a spastic hand. The ability to generate this level of force without excessive pressure highlights the actuator's efficiency and potential for assisting with hand rehabilitation. Importantly, the measured force aligns with the mechanical demands of overcoming spasticity in stroke patients, where excessive muscle tone can inhibit hand extension. The findings suggest that the actuator can provide gentle yet effective assistance, improving hand mobility without causing discomfort or strain. This makes the actuator a promising component for future rehabilitation devices aimed at restoring motor function in individuals with impaired hand movements due to neurological conditions.

These findings collectively demonstrate the successful application of finite element modelling and bioinspired design principles in the development of soft pneumatic actuators. The optimized design parameters, effective motion range, and force output suggest that the BSPA could significantly contribute to advancements in soft robotics, particularly in medical rehabilitation technologies.

5. 1. Limitation of The Design

Despite the promising outcome of the soft pneumatic actuator design and simulation, limitations must be acknowledged to gain a more realistic view of its actual implementation. Firstly, the durability of the actuator materials is a challenge. Although materials such as silicone (e.g., Ecoflex) exhibit very good flexibility and skin compatibility, they tend to suffer from fatigue, tearing, and degradation over time with repeated pressurization and bending cycles. This would compromise the actuator's long-term performance and reliability for practical rehabilitation applications. Secondly, the actuator design's scalability remains limited, having been designed based on average hand size. In a clinical setting, actuators must be adaptable to accommodate different hand sizes—from pediatric to geriatric patients—without compromise in performance and comfort. Modular or size-adaptive designs may have to be created to accommodate a larger user population. Furthermore, clinical integration is also beset by several practical challenges, like maintaining user comfort during extended wear times, hygiene, and cost reduction. The system must be lightweight, non-irritating to the skin, and simple to operate with little training. In addition, incorporating feedback mechanisms (e.g., EMG or sensor-based control) may introduce complexity and cost, potentially excluding its use in low-resource environments. These limitations refer to the need for further development and real-world testing to optimize the actuator system for more widespread clinical use.

To maximize the translational utility of the proposed BSPA system, its translation into a real clinical rehabilitation context must be considered. The potential of the actuator to induce recovery of upper limb movement, particularly in stroke survivors, must be expanded and validated through controlled clinical trials. For instance, inclusion in task-oriented rehabilitation therapy regimens such as repetitive reach and grasp exercises can be aimed at being used in addition to conventional physiotherapy. As demonstrated in Nuckols et al.'s (2020) research, soft robotic gloves used in stroke rehabilitation had significant gains in motor function measured using standardized clinical instruments like the Fugl-Meyer Assessment (FMA) and Box and Block Test (BBT). Similarly, the BSPA may be tried out on stroke patients with mild to moderate upper-limb impairment to check its potential for range of motion, muscle reactivation, and user satisfaction. Clinical implementation would also be facilitated by the inclusion of patient-specific customization (e.g., setting pressure thresholds or range of motion) for safety and comfort. Furthermore, feedback from the clinician and occupational therapist can also enable adaptation of the control interface for easy application in both in-clinic and home settings. A well-designed pilot study with randomized control groups would provide the required clinical data and validation to justify inclusion into official rehabilitation protocols.

6. Conclusion

This study presented the design, modelling, and analysis of a bioinspired soft pneumatic actuator (BSPA) for straightening applications, utilizing finite element methods (FEM) to simulate its performance. Key design parameters such as actuator width, wall thickness, chamber dimensions, and actuation angles were systematically optimized to enhance the mechanical efficiency of the actuator. Simulation results demonstrated that the actuator achieved a 90° extension at a pressure of 110 kPa and produced a reaction force of 3N at 80 kPa, sufficient to fully open a hand when integrated into a soft robotic glove. These findings underscore the potential of bioinspired soft actuators in medical and rehabilitative applications, particularly in assisting stroke survivors with hand mobility impairments.

The theoretical and methodological implications of this research lie in the use of finite element modelling to optimize soft pneumatic actuators. By leveraging FEM, this study not only provides accurate predictions of actuator behaviour under various loading conditions but also highlights the importance of bioinspired design principles in soft robotics. The methodology developed in this work can be applied to other soft actuator designs, offering a scalable framework for simulating complex mechanical deformations. Moreover, the combination of SolidWorks for design and Abaqus CAE for simulation creates a robust pipeline for evaluating actuator performance before physical prototyping, reducing the cost and time required for experimental testing.

The practical implications of this research are significant, particularly for rehabilitation technology. The BSPA's ability to replicate natural hand movements and generate sufficient force for hand extension indicates its suitability for use in soft robotic gloves designed to assist individuals with motor impairments. This is especially relevant for stroke survivors, where traditional rehabilitation techniques may be insufficient for restoring hand function. The actuator's efficiency at moderate pressures ensures that it can be safely integrated into wearable devices without risk of injury or excessive energy consumption, making it a viable solution for long-term therapeutic use.

From a social and environmental perspective, the development of soft pneumatic actuators like the BSPA offers several advantages. Socially, this technology has the potential to improve the quality of life for individuals suffering from hand mobility issues, promoting greater independence and reducing the burden on caregivers. Environmentally, the use of soft, compliant materials in the actuator design reduces the reliance on rigid and energy-intensive materials typically used in robotics. The relatively low operating pressure also suggests lower energy demands, contributing to more sustainable robotic solutions for healthcare and rehabilitation.

Despite its promising outcomes, this study is not without limitations. The simulations, while highly informative, do not fully capture all real-world factors such as material fatigue, long-term wear, and the effects of repeated actuation cycles. Additionally, the focus on a single actuator design limits the generalizability of the findings to other soft pneumatic actuators with different configurations. Future work should explore these aspects through experimental validation, ensuring that the actuator's performance remains consistent over prolonged use and in more complex environmental conditions. The designed BSPA is different from conventional soft actuators in structure and functionality. Unlike typical bending actuators, which mostly restrict themselves to curling or grasping motion, the BSPA is specifically designed to enable straightening motion, which is critical in finger extension of post-stroke patient rehabilitation or patients with neuromuscular impairments. This directional movement is enabled by the half-round cross-sectional area of the actuator, which deliberately channels pneumatic pressure along a specific path and thus generates more accurate and efficient straightening. In contrast, traditional cylindrical or solely soft actuators typically experience isotropic expansion, which might lead to unstable or imprecise movements. Furthermore, the BSPA has a wide base and supporting layers that restrict unwanted deformation, something that may not be present in simpler soft robot designs. Compared to similar soft robotic gloves by Polygerinos et al. (2015) or Nuckols et al. (2020), which make use primarily of fiber-reinforced or fully flexible structures for gripping, the structural asymmetry and specific motion control of the BSPA represent a significant advancement. This new design provides more accurate actuation for finger extension, which is under-addressed in most systems available today and critical to the restoration of full hand function.

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