Design and optimization of a linear fiber-reinforced soft actuator for improved linear motion performance

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ABSTRACT

The demand for safe and flexible actuators has increased as traditional actuators pose safety risks due to their rigid materials, especially in applications requiring human-machine interaction. This study focuses on designing and optimizing a linear fiber-reinforced soft actuator to enhance linear motion performance while maintaining safety and flexibility. Finite element method (FEM) analysis was used to evaluate the effects of varying key design parameters, including core radius, actuator length, and core wall thickness. The analysis revealed that increasing the core radius leads to greater linear extension, while increasing the actuator's length and wall thickness reduces extension. Among the tested designs, the R10 design exhibited the highest linear extension, with a 44.41% increase in length compared to the original design. However, the R10 design also showed undesirable bulging at the free end under pressure, which necessitated further optimization. By increasing the thickness of the sheath wall, the bulging was reduced, and the optimized design achieved a 34.53% increase in extension. This study highlights the significance of parameter optimization in fiber-reinforced soft actuators to achieve superior linear motion performance. Future work will explore further improvements in structural stability, sensor integration for precise control, and advanced fabrication techniques for better customization and durability.

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1. INTRODUCTION

In recent years, there has been an increase in demand for solutions to user injuries produced by standard stiff actuators. Conventional robots, which consist of mechanical pieces that move and are controlled by typical actuators, pose a safety risk to people [1]-[15]. Traditional actuators have the ability to withstand more pressure and provide higher output force, speed, precision, and accuracy in comparison to soft actuators [16]-[21]. Nevertheless, the inflexible nature of the material poses a risk for interactions between users and machines, particularly in unorganised settings. The inflexibility of conventional actuators might be hazardous to users due to the use of hard materials. Implementing their rigid physical properties in various situations, particularly unstructured ones, poses significant challenges. Therefore, soft actuators were implemented as a solution to address the limitations of conventional actuators. Soft actuators consist of pliable materials that can be manipulated using techniques like pneumatic actuation, which involves applying pressure to internal chambers to alter their shape and induce movements like bending. Thus, soft actuators are more advantageous and secure for usage in user-machine interactions that demand them. The current challenge with soft actuators is the difficulty in accurately modelling and controlling their motion [22]-[26]. Prior to implementing sensors and controllers into the soft actuators, it is necessary to analyse, optimise, and characterise the design of the soft actuators to ensure the desired output performance. This process ensures that the soft actuators are tailored to meet the requirements of a certain application.

The fiber-reinforced actuators are a type of soft actuator, that have been recently created by many research groups worldwide [27]-[31]. Fiber-reinforced actuators, in operating principle, such as the PneuNet actuators, operate on pressurized air but vary in design and thus differ in outcome [1]-[3]. Figures 1 and 2 show the standard architecture of a fiber-reinforced actuator that comprises a tubular-geometry, elastic-polymer body enveloped with inextensible reinforcements, the strain-limiting base layer, and the spirally aligned fibers on the exterior [31]. The elastomer body has a large chamber in the middle that behaves just like a balloon such that when it is pressurized, it stretches in every direction. The fibers prevent the actuator from excessive deformation as they restrict it from expanding radially and restrict deformation in ways designed to create the required deformation pattern.

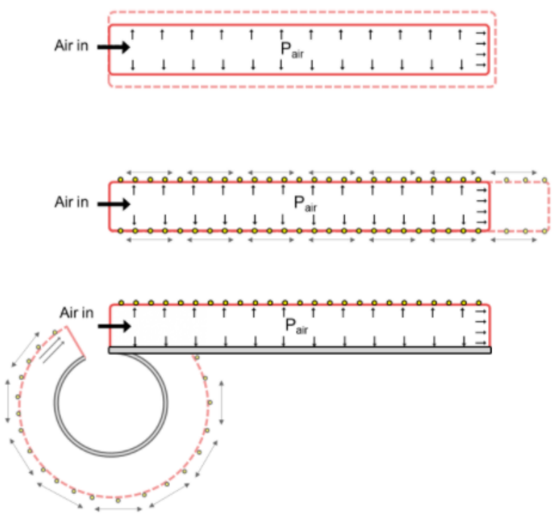

Figure 1. Fiber-reinforced design principal operation when pressurized

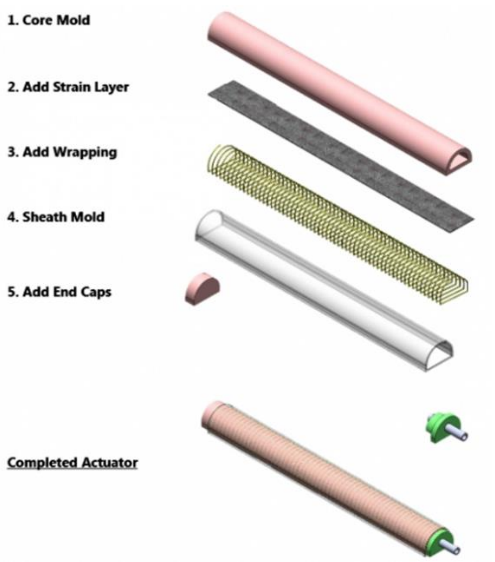

Figure 2. Fiber-reinforced components

In addition, the strain-limiting layer, which is made from an inextensible material on the bottom, stops the actuator from stretching in that layer's covered area. One end will extend in an axial direction, and the other will not, and this causes the actuator to bend when pressurized. Fiber-reinforced actuators have the ability to elongate, rotate, enlarge, and flex by making changes to the strain-limiting materials, allowing them to follow a desired kinematic trajectory. As reported in the Soft Robotics Toolkit developed by Harvard University and Trinity College Dublin [31], thread-wrapping is labor-intensive, but it has better customizability than the traditional design. Different thread materials can be used, but Kevlar is recommended for durability. The smaller the spacing of the fiber wrapping, the lower the pressure needed to achieve the same degree of bending. When the fibers are spaced far apart, the spaces of the threads show a noticeable bulge that expands radially. Based on Figure 3, symmetrical, double-helix wrappings restrict the actuator from radial expansion and only enable axial expansion. The insertion of a strain-limiting layer restricts one end of the actuator from expanding, which makes the actuator bend. The different settings of the wrappings and strain-limiting, as seen in Figures 4 to 6, allow other motions to be produced. Fiberglass fabric is most used, but if used as the strain-limiting layer, it can be molded together with the main chamber, and the stray fibers cause leakage. Similar thin material that is not elastic, such as paper, can serve as a replacement. Paper, unfortunately, is not as porous as fiberglass, so it does not sink well into the silicone. Holes or slits should be cut in the middle of the paper so that the silicone can penetrate both sides.

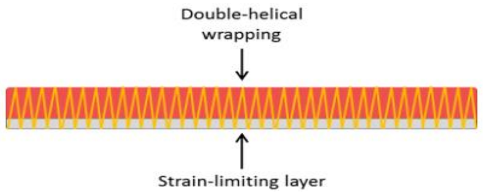

Figure 3. Fiber-reinforced design for bending motions

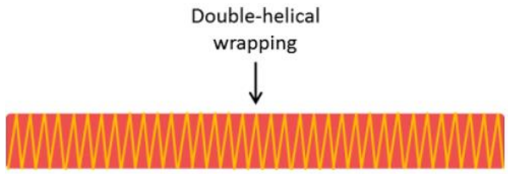

Figure 4. Fiber-reinforced design for extending motions

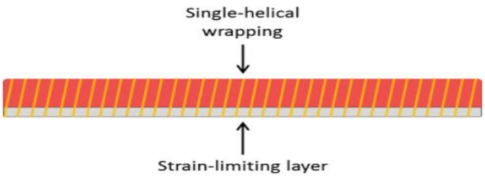

Figure 5. Fiber-reinforced design for twisting and bending motions

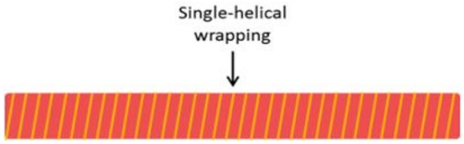

Figure 6. Fiber-reinforced design for twisting and extending motions

In addition to modifying the specifications of the strain-limiting elements, the geometry of the actuator will result in different effects of bending performance, i.e., shape and parameters. The commonly used cross-sectional designs in soft actuators are circular, rectangular, and semi-circular, as shown in Figure 7. The circular actuator can apply the highest bending torque with the same input pressure, but it is the least efficient because it is resistant to bending among the designs. In terms of efficiency, it is about the same for both rectangular and semi-circular designs. However, when pressurized, the rectangular-shaped design changes into a quasi-circular shape, whereas the circular and semi-circular designs preserve their initial structure. A rectangular-shaped actuator has a high risk of stress due to sharp corners, resulting in fatigue or failure. Based on the analysis by [31] in Figures 8(a)–(c), the design of the actuator could be optimized by taking into consideration the following parameters: i) actuator radius, ii) actuator length, and iii) actuator walls thickness. Figure 8(a) demonstrates how increasing the actuator radius decreases the required pressure to achieve a certain degree of bending, which enhances linear motion performance. Figure 8(b) focuses on the impact of actuator length, showing that a longer actuator requires less pressure to reach similar bending degrees, though it does not significantly affect the force produced. Figure 8(c) examines the effect of core wall thickness, indicating that thicker walls demand higher pressure to achieve the same level of extension but provide better resistance to deformation. These subfigures collectively highlight the importance of balancing these parameters, i.e.,: radius, length, and wall thickness, in order to optimize the performance of linear fiber-reinforced soft actuators. Figures 9(a)-(e) illustrates the fiber-reinforced molds, and the fabrication process involved in developing the soft actuator [31]. The fabrication process begins with creating the primary body of the actuator, which is molded around a semi-circular rod. This mold is essential as it forms the hollow central chamber, providing support and ensuring precise alignment during the assembly of the strain-limiting layers. The fiber reinforcements are then strategically wrapped around the actuator, restricting unwanted radial expansion and ensuring that the extension occurs in a controlled axial direction. The outer silicone sheath, molded over the fibers, further reinforces the structure, and encapsulates the entire actuator, providing durability and maintaining structural integrity during pressurization. This fabrication method ensures that the actuator can achieve the desired linear motion with minimal deformation, as highlighted by the various design optimizations throughout the study.

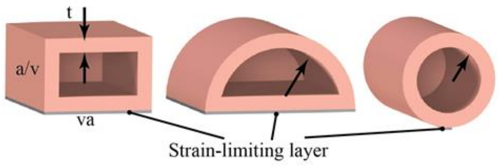

Figure 7. Common cross-sectional shapes in soft actuator designs; circular, rectangular, and semi-circular

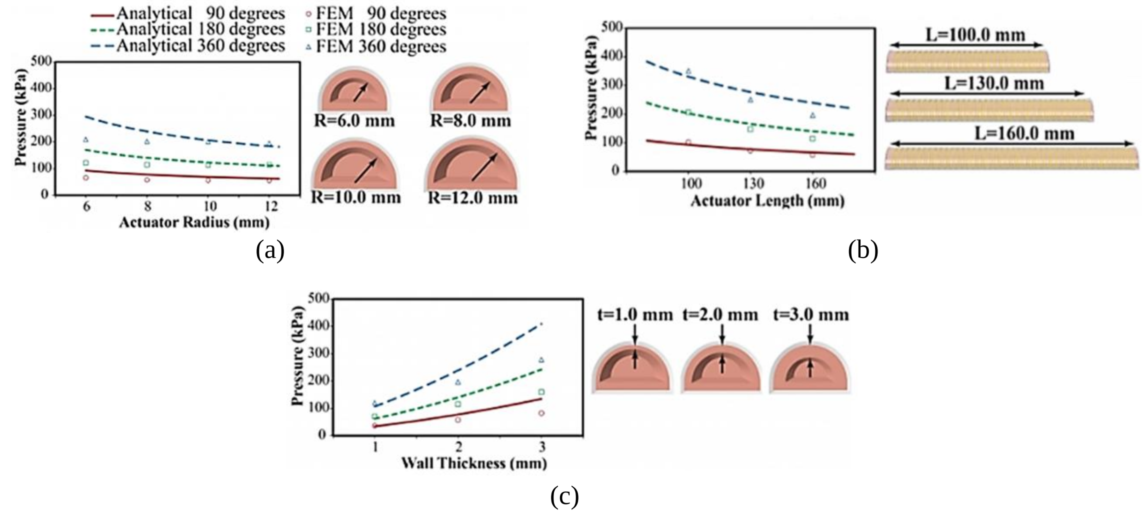

Figure 8. Analysis of optimizing parameters for linear fiber-reinforced soft actuators of; (a) actuator radius, (b) actuator length, and (c) actuator walls thickness

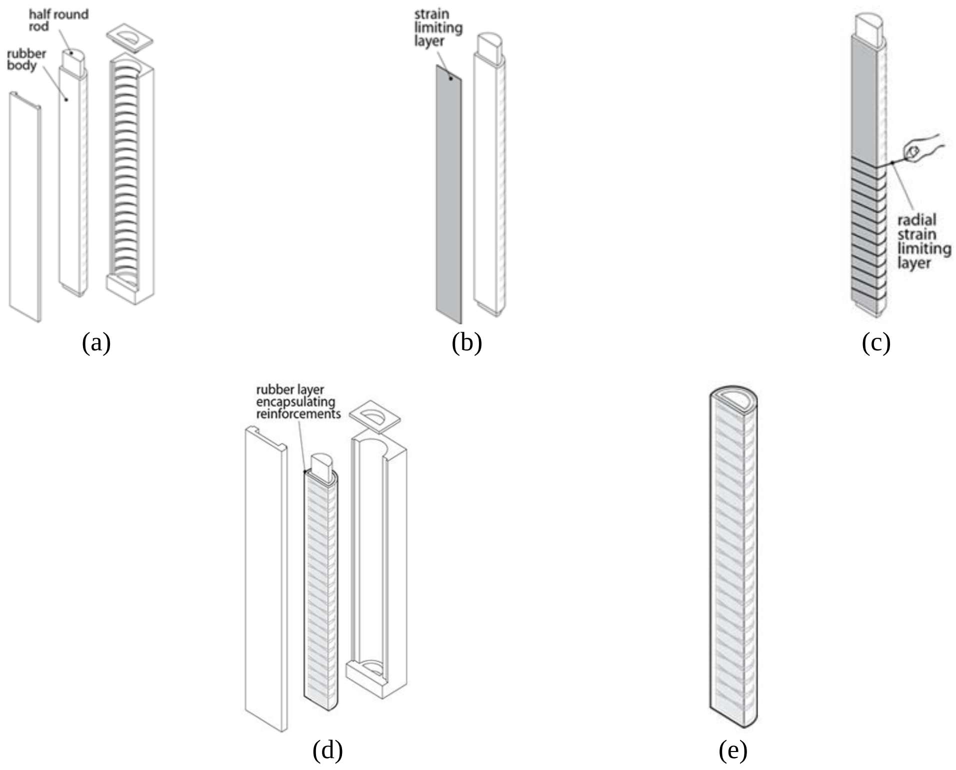

Figure 9. Fiber-reinforced molds and fabrication process of; (a) semi-circular rod mold, (b) assembly of the strain-limiting layers, (c) the fiber reinforcements wrapped around the actuator, (d) the outer silicone sheath, molded over the fibers, and (e) completed linear fiber-reinforced soft actuator [31]

Hence, the objective of this study is to develop a linear fiber-reinforced soft actuator that exhibits excellent linear motion capabilities. This will be achieved by employing finite element method (FEM) analysis to optimise the actuator design through parameter variations. The resulting designs will then be evaluated and analysed based on their maximum extension to determine the most effective design for linear motion performance. The soft actuator primarily utilises liquid silicone, specifically Ecoflex 00-30, as its study material. The soft actuator design undergoes finite element analysis (FEA) using the Abaqus software. The soft actuator subjected to multiple input pressures to evaluate its performance, specifically emphasising the extension linear motion.

2. LINEAR FIBER-REINFORCED SOFT ACTUATOR DESIGN

This research aimed to develop a linear fiber-reinforced soft actuator for linear motion performance. The linear fiber-reinforced soft actuators were designed using the Abaqus FEA software. There are only three parts in the design: i) main body (core), ii) fibers (wrappings), and iii) sheath. The soft actuators were designed using the Abaqus FEA software using the parameters shown in Table 1 and Figure 10.

Table 1. Parameters of the body of the fiber-reinforced design

Parameters of body	Dimension (mm)
Radius of core, *R*	6
Length of actuator, *L*	100
Thickness of core wall, *T*	1

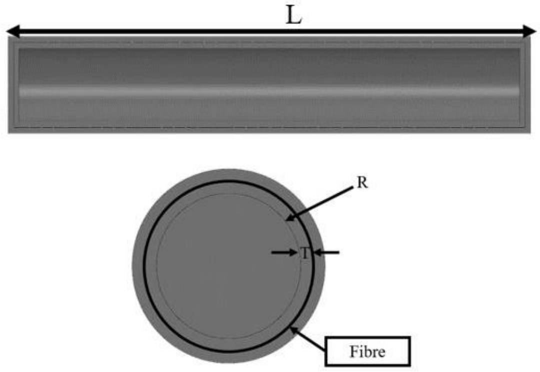

Figure 10. Parameters of fiber-reinforced design

The parameters chosen for the fiber-reinforced design are the radius of core, *R*, length of actuator, *L*, and thickness of core wall, *T*, as shown in Table 2. The original *R*-value is 6 mm, and the dimensions used for the optimization will be 8 mm and 10 mm. The original *L*-value is 100 mm, and the dimensions used for the optimization will be 120 mm and 140 mm. The original *T*-value is 1 mm, and the dimensions used for the optimization will be 2 mm and 3 mm Additionally, for each parameter, there are fixed parameters as shown in Table 2. Table 3 and Figure 11 display the fiber parameters assessed in this study. The values of parameters *r* and *l* are modified based on the alterations in the dimensions of the outer surface of the main body, while keeping the angle of the fiber windings constant. The fiber utilised for the simulation possesses a diameter of 0.3347 mm. The optimised designs were subjected to three simulations using the Abaqus software to verify the accuracy of the acquired simulation results. Table 3 shows that a total of seven (7) designs were simulated and analysed. These designs include the original design with parameters *R*=6, *L*=100, and *T*=1, the R8 design with *R*=8, *L*=100, and *T*=1, the R10 design with *R*=10, *L*=100, and *T*=1, the T2 design with *R*=6, *L*=100, and *T*=2, the T3 design with *R*=6, *L*=100, and *T*=3, the L120 design with *R*=6, *L*=120, and *T*=1, and the L140 design with *R*=6, *L*=140, and *T*=1, respectively as shown in Table 3. The average of the data is taken as the result. Lastly, the best design is chosen based on the results and optimized until it shows the greatest output.

Table 2. Optimisation parameters of the fiber-reinforced design

Parameters of body	Dimension (mm)			Fixed parameters
	Original	Varied		
Radius of core, *R*	6	8	10	*L*=100, *T*=1
Length of actuator, *L*	100	120	140	*R*=6, *T*=1
Thickness of core wall, *T*	1	2	3	*R*=6, *L*=100

Table 3. Seven designs and it's parameters

	Designs						
Parameters of fiber	Original	R8	R10	T2	T3	L120	L140
Radius of fiber, *r* (mm)	7	9	11	8	9	7	7
Length of fiber, *l* (mm)	98	98	98	98	98	118	138
Angle of fiber, *a* (º)	3	3	3	3	3	3	3

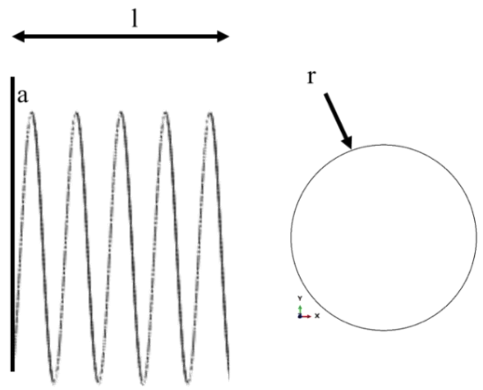

Figure 11. Fiber parameters

The soft actuator's design process was executed with the Abaqus FEA software. The designs were created based on the specifications provided in Table 1. Figure 12 depicts the structure of the soft actuator that is reinforced with fibers, whereas Figure 13 illustrates the internal components of the soft actuator. The design comprises three components: the core, the exterior layer known as the sheath, and the wrappings made of fiber. The fiber is wound around the outer surface of the main body in an asymmetrical, double-helical pattern at a little angle to avoid radial expansion. This causes the fiber to extend in the axial direction when pressure is applied. The wrapped fiber and main body are encapsulated with another 1 mm silicone layer, called the sheath, to reinforce the security of the wrappings onto the main body. There are several common shapes for the core: circular, rectangular, and semi-circular. The circular shape has a significant resistance to bending, rendering it the most efficient configuration for extending soft actuators. Under pressure, the rectangular cross-section undergoes deformation and takes on a quasi-circular shape, whereas the other two types of cross-sections retain their original shapes. The presence of sharp corners on the rectangular and semi-circular actuator might potentially heighten the likelihood of stress concentrations, leading to fatigue or failure. Hence, the research has opted for a circular shape design.

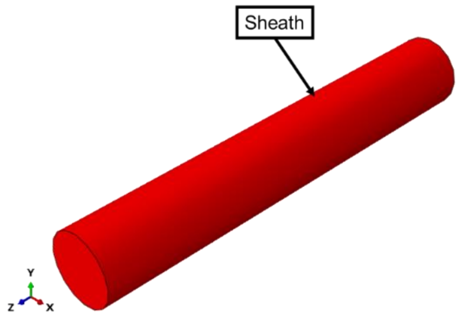

Figure 12. Fiber-reinforced soft actuator design

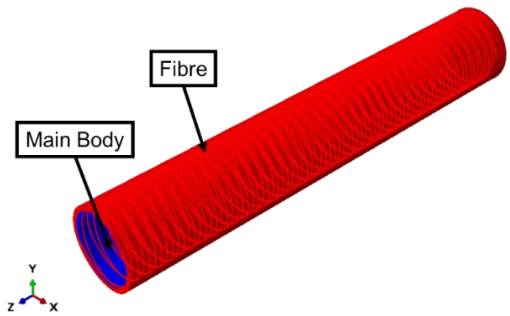

Figure 13. Fiber-reinforced inner parts design

3. DESIGN PERFORMANCE USING FINAL ELEMENT METHOD ANALYSIS

The seven designs of the soft actuator, as shown in Table 3, were simulated using the Abaqus FEA software. Figure 14 showed the fiber-reinforced soft actuator design and was simulated using the Abaqus software. As stated previously, the design consists of two ends, there is a fixed end and a free end. The actuator will extend linearly in the Z-axis direction. This software will evaluate the extension at multiple steps in which the pressure will be divided into these steps. For example, this simulation has 100 steps; hence, the extension will be evaluated at each step with 0.0001 MPa increment or 100 Pa per step until it reaches the maximum input pressure, 0.01 MPa. The original design has the base parameters R=6 mm, L=100 mm, and T=1 mm. Each parameter was optimized to analyze which parameters would affect the extension to increase the extension. Figure 15 demonstrates that the R10 design exhibits the highest level of extension, measuring at 44.41%, whilst the T3 design displays the lowest level of extension, measuring at 12.43%. The L140 possesses the greatest elongation, with a total length of 162.69 mm if subjected to pressurisation. However, the percentage of extension only increases by 16.21% compared to the R10 design, which experiences a 44.41% increase in length before being pressurised. The findings indicate that when the value of *R* increases, the extension, *U* also increases. Conversely, when the values of *T* and *L* increase, the extension, *U* decreases, as shown in Figure 14. The R10 design is the most superior design overall. The R10 design has a bigger advantage compared to the original design, since it resulted in a 44.41% increase in length, compared to the previous design's 17.29% increment. Nevertheless, the drawback entails a design issue characterised by an undesirable protrusion in the design. As a result, R10 is selected for further optimisation in order to enhance the design.

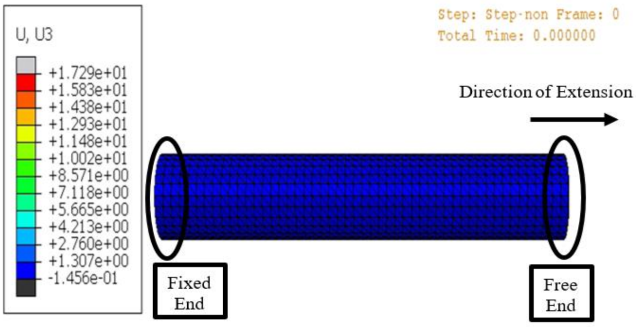

Figure 14. Fiber-reinforced soft actuator simulation

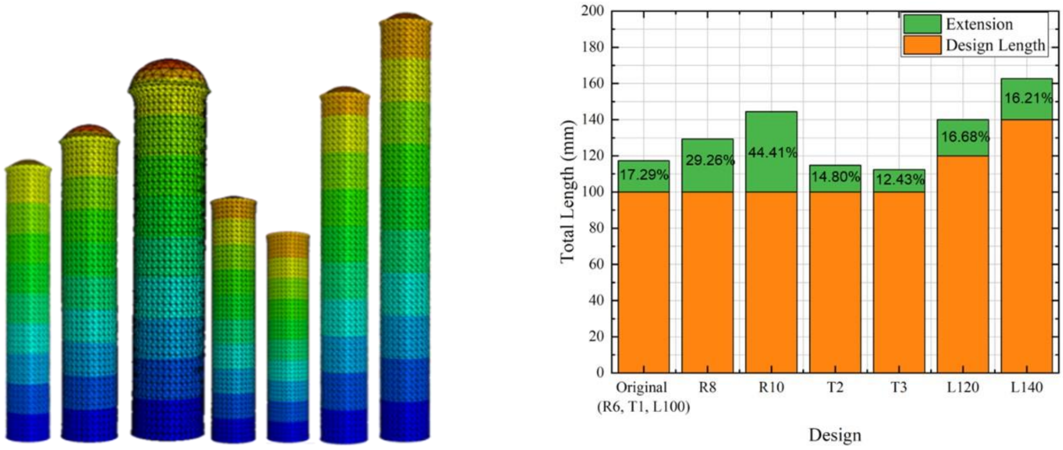

Figure 15. Results of simulation vs graph of total length for each design

The issue with the R10 design could potentially be attributed to the slender walls, which lack any form of support or constraints in contrast to the region where the fibers are encased. Thus, the R10 design is further optimized. To maintain the length of the actuator, *L* at 100 mm, the proposed solution is to increase the thickness of the walls on the free end of the Sheath from 1 mm to 5 mm which will lead to a need to reduce the length of the main body and fibre from 98 mm to 94 mm since these parts lies inside the Sheath. The changes are simulated, and the outcome is analysed. Figure 16 displays the outcome prior to and during the optimisation of the R10 design. The enhanced R10 design exhibits a more evenly distributed pressure on the body compared to the previous R10 design, which exerted focused pressure just at the free end. Nevertheless, the maximum extension decreased because bigger walls necessitate greater pressure for activation. According to Figure 17, the R10 design has the greatest amount of extension, with a 44.41% increase, while the original design has the smallest amount of extension, with a 17.29% increase from its initial length before being pressurised. The optimised R10 design can achieve a maximum extension of 34.53% from its initial length after pressurisation. Nevertheless, the optimised design minimises its expansion in comparison to the R10 design. According to Figure 18, the extension of the R10 design has increased by 27.12% compared to the original design. However, there is a decrease of 9.88% from the R10 design to the optimised R10 design, while still maintaining a 17.24% increase compared to the original design. Even though the R10 design produces the most extension, the optimised R10 design is ultimately selected as the final design due to the substantial reduction in undesirable bulging.

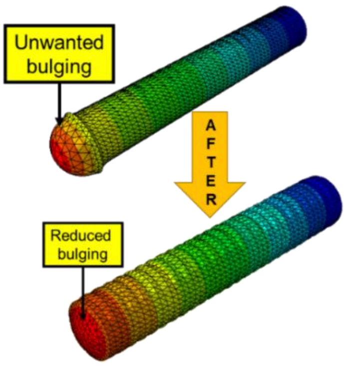

Figure 16. Result after optimizing R10 design

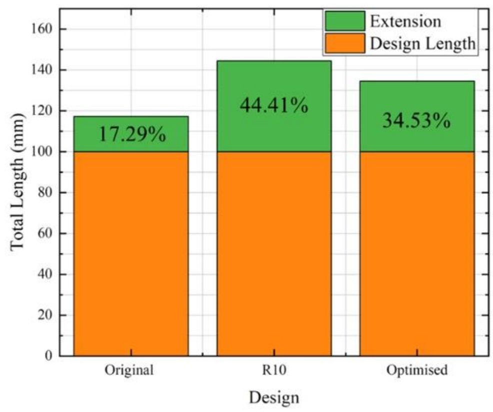

Figure 17. Graph of total length for original, R10, and optimized design

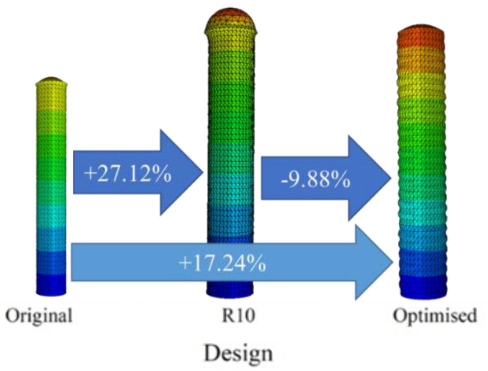

Figure 18. Comparison of improvements in the extension of original, R10, and optimized design

4. CONCLUSION

The objective of this study was to design and optimize a linear fiber-reinforced soft actuator to improve linear motion performance This is achieved by optimising the design through the manipulation of actuator parameters using FEM analysis. This study focuses on optimising the design in terms of linear motion performance, specifically by assessing the maximum extension. The soft actuator was specifically built with a circular-shaped cross-section that exhibits a high degree of resistance to bending, thereby making it the most efficient shape. An addition of symmetrical, double-helical fiber windings at a slight angle prevents the actuator from expanding radially—these results in an extension in the axial direction when pressurized. The varied parameters were radius of core, *R*, the thickness of the core wall, *T*, and length of the actuator, *L*. Simulation results showed that when radius of core, *R* and length of the actuator, *L* increase, *U* increases; and when *T* increase, extension, *U* decreases. Nevertheless, it can be concluded that when *L* increases, the amount of extension decreases in terms of the percentage of extension. The design, R10, which exhibited a notable bulging at the free end due to concentrated pressure, was selected for further optimisation to address the design concerns. Hence, a proposed approach to enhance the R10 design involves increasing the thickness of the sheath wall at the free end side from 1 mm to 5 mm, while keeping the overall optimised parameters unchanged. The designs were assessed and examined under pressure ranging from 0 to 0.01 MPa. When comparing the original design to the R10 design, the extension motion has increased by 27.12%. However, there is a 9.88% decrease in the design from R10 to the optimised R10. Nevertheless, there is a notable 17.24% rise compared to the initial design, with the R10 design producing the greatest extension. The optimised R10 design is selected as the final design due to the substantial reduction in undesirable bulging compared to the original R10 design. Although the optimized R10 design displayed a slightly reduced extension compared to the original R10, it was ultimately selected for its improved structural stability. The findings underscore the importance of optimizing design parameters to enhance the performance of fiber-reinforced soft actuators for linear motion applications.

While this study has provided significant insights into the optimization of linear fiber-reinforced soft actuators, several areas warrant further exploration. Future work will focus on incorporating stiffer materials for the sheath to reduce localized stress concentrations and further minimize bulging effects. Additionally, implementing advanced control strategies will be crucial to fine-tune the actuator's linear motion in real-world applications. Another avenue for investigation is the integration of sensors to provide feedback control for improved accuracy and responsiveness. Finally, future studies could explore the use of multi-material 3D printing technologies to enhance the customization of actuator designs, potentially leading to improvements in both performance and manufacturing efficiency.

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