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Material-Driven Mechanical Programming of Soft Robotic Tentacles

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***Abstract*— Soft robotic grippers with stochastic and topological grasping capabilities can be highly desirable for gentle contact and interaction with fragile objects of various shapes. In this study, we developed soft tentacles using silicon elastomeric material with an embedded pneumatic channel, which generates desirable three-dimensional (3D) curling deformation under pneumatic pressure. Additionally, various ratios and geometrical distributions of two silicon materials, which differ primarily in stiffness, were investigated to determine their effect on grasping efficiency. The tentacle's grasping performance was systematically tested across multiple tentacle designs and grasping strategies. Results showed that optimizing the combination of softer elastomers with stiffer materials significantly improved the tentacle's ability to securely grip and carry loads while maintaining gentle contact with objects (up to 5 kg). The pneumatic tentacle's simple control mechanism and versatility in handling objects of various shapes and sizes offer a low-cost, adaptable solution for future applications in soft robotics.**

I. INTRODUCTION

In nature, some organisms have developed remarkable grasping abilities. With its highly flexible arms that can bend, twist, and stretch in multiple directions, the octopus excels at manipulating objects in confined spaces [1]. Existing research on soft robotic grippers, including nanofiber-reinforced actuators for manipulating live jellyfish [2] and high-speed soft picking solutions for the food industry [3] demonstrates the advanced capabilities of soft grippers. Therefore, designing soft grippers for interactions with vulnerable and irregular objects needs to incorporate flexible deformation capabilities [4]. Additionally, mechanical programming of these soft grippers could enhance stability [5] and flexibility [6] [7] for lifting and transporting objects.

Recent advancements in soft robotics have explored the use of single elastomeric material [8] [9] with monolithic designs [10], or in combination with stiffer material[11] [12], to create structures with embedded channels, which deform and generate motion through controlled inflation, enabling movements such as bending and gripping. However, the grippers they designed are primarily effective for grasping round objects and cannot adapt to irregular voids or perform stochastic grabbing like tentacle-inspired systems.

Research on tentacle soft actuators has focused on creating highly flexible structures capable of more complex 3D deformations. Connolly et al. used fiber reinforcement to control the movement direction of soft actuators, demonstrating that varying fiber angles could be used to tune different types of motion such as twisting, expansion, and contraction [13]. Similarly, Martinez et al. developed soft tentacle actuators with three pneumatic channels (PneuNets) and controlled their movement by selectively inflating different channels to achieve 3D actuation [14]. While these efforts show promising advancements in soft robotics, they primarily focus on external reinforcements or selective inflation strategies. There remains limited exploration of how the internal geometrical distribution of materials with varying stiffness, such as combinations of softer and stiffer elastomers, influences 3D deformation and load-bearing capacity.

Fig. 1. Off-axis inflated Ecoflex tentacle gently grasps a flower (top) with its corresponding horizontal filling method(bottom).

In this paper, we address this problem by investigating the effects of different material ratios and geometrical distributions in pneumatic soft actuators. Specifically, we explore how dual-material elastomers, with varying stiffness, can be spatially arranged to enhance the tentacle's ability to perform complex 3D movements and significantly improve its load-

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bearing capabilities. Our results show that the tailored tentacle can adapt to a wide range of object shapes and stiffness with the correct material composition and arrangement, and lift loads of up to 5 kg. This demonstrates that soft tentacles can manipulate objects with greater flexibility, and the ability to carry heavier loads is highly dependent on the grasping method employed.

II. DESIGN AND MANUFACTURING

A. *Design Principle*

The soft actuator is designed using the principle of mechanical programming to achieve specific behavior through inherent geometry and variations in material composition. The design begins with an elliptical tube composed of elastomeric material with an off-centered air channel, which undergoes asymmetric expansion when inflated. The asymmetry induces a 3D chiral twisting deformation due to uneven material expansion. When air is pumped into the air channel, the thinner wall deforms more readily than the thicker wall, leading to a helical shape in the overall structure. This geometrical twisting enables active entanglement, allowing the actuator to perform stochastic, topological grasping, where the actuator can adapt to irregularly shaped objects, entangling and securing them without the need for precise control or predetermined contact points. Figure 2 shows a schematic sketch.

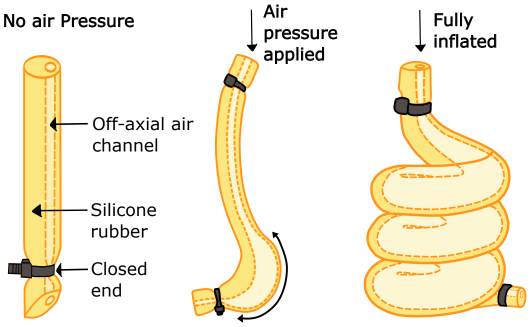

Fig. 2. The mechanical programming principle of a soft actuator with an off-axis air channel, demonstrated using a pure Ecoflex tentacle. In the unpressurized state (left), the channel is off-axis along the tentacle's length. When pneumatic pressure (middle) is applied, the channel's asymmetry causes the tentacle to bend and curl. The tentacle adopts a helical shape when fully pressurized (right).

B. *Single Material Tentacle*

In this section, we explore the use of two distinct silicone materials—Ecoflex^{TM} 00-30 (Smooth-On$^{®}$, referred to as Ecoflex in this article) and Dragon Skin^{TM} 10 Slow (Smooth-On$^{®}$, referred to as Dragon Skin)—for fabricating soft tentacles designed to exhibit twisting behavior. The primary motivation for using different materials is to investigate how varying material properties influence the performance and behavior of the tentacles and to identify key considerations for fabricating tentacles for more complex designs.

The materials chosen, Ecoflex and Dragon Skin, differ significantly in their physical properties, including viscosity, tensile strength, and flexibility, which are detailed in Table I. These differences are expected to affect how each material responds to pneumatic pressure and how well it maintains structural integrity during deformation [15]. By comparing the performance of tentacles made from these materials, we aim to gather insights that will inform future design and manufacturing practices. The manufacturing process begins with creating a small opening at the top of a horizontally aligned mold. Silicone elastomer is then injected through this opening to minimize wall contact and reduce the risk of voids or large air bubbles. This horizontal filling approach helps mitigate gravitational issues that might arise if the mold were filled vertically, as shown in Fig. 1. Additionally, to further reduce air bubbles, techniques such as slow injection and expulsion of residual bubbles through the side of the mold were employed [16].

The tentacles are designed with an off-center air channel of 3 mm in diameter and are produced in two outer diameters: 6 mm and 11 mm. The length of each tentacle is 20 cm. The outer diameter variations are tested to evaluate their impact on the tentacle's twisting performance. This investigation is crucial for understanding how diameter changes affect the tentacle's behavior under pneumatic pressure.

1) Ecoflex: Ecoflex is a platinum-catalyzed silicone rubber renowned for its exceptional flexibility, strength, and durability, making it a representative elastomer widely used in soft robotics [18][19]. Due to its high tensile strength and tear resistance, an Ecoflex tentacle can expand and curl when air is pumped into it. It forms a neat spiral shape only under the off-axis air channel principle without external influences or specialized design modifications. Under a pressure of approximately 170kPa, the tentacle's inner diameter expands from 3mm to 20mm, representing an almost sevenfold increase over its original size.

Molds of two different diameters, 6mm and 11mm were tested for the Ecoflex material, revealing that the smaller diameter mold tends to result in multiple failures. Filling the thinner molds is more challenging, and the tentacles are more likely to be damaged during demolding as shown in Fig. 3. Furthermore, the reduced wall thickness shortens the lifespan of the tentacle. The thinner-walled tentacles do not fully return to their original shape, resulting in surface wrinkles.

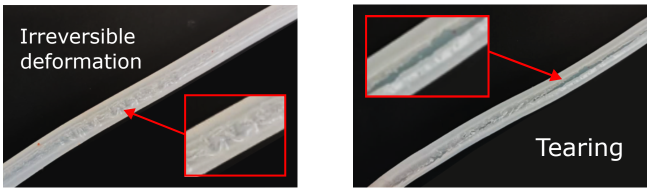

Fig. 3. Challenges for creating Ecoflex tentacles of smaller diameter. Images of irreversible deformation (left) and tearing (right) of the thinner wall.

In addition to the abovementioned malfunctions, we also noted that pure Ecoflex tentacles easily lose their curled shape when subjected to external forces. To investigate this issue, we experimented with tentacles made entirely from

TABLE I
MAIN CHARACTERISTICS OF MATERIALS USED [17]

Material	Mixed Viscosity	Cure Time	Shore Hardness	Tensile Strength	100% Modulus	Elongation at Break	Die B Tear Strength
Ecoflex$^{\text{TM}}$ 00-30 (Smooth-On$^{®}$)	3000 cps	4 hours	00-30	200 psi	10 psi	900%	38 pli
Dragon Skin$^{\text{TM}}$ 10 Slow (Smooth-On$^{®}$)	23000 cps	7 hours	10A	475 psi	22 psi	1000%	102 pli

Dragon Skin, a material with higher mechanical resistance, to assess its potential for better shape retention and load-bearing capacity.

2) Dragon Skin: Dragon Skin is a high-performance silicon rubber. The material detail compared to Ecoflex is listed in Table I. Due to the higher stiffness of Dragon Skin, the tentacle demolded from the larger-diameter mold hardly inflates when air is introduced. In contrast, the tentacle from the smaller-diameter mold can be inflated and demonstrates curling properties, as shown in Fig. 4. However, numerous air bubbles trapped inside the silicone create multiple weak spots. These bubbles cause uneven wall thickness, and when pressure is applied, many of these weak spots burst, leading to the failure of the tentacle.

Fig. 4. Two fully inflated tentacles with single material and off-axis air channel. Ecoflex, with its higher tensile strength enables a neat spiral shape (left) and Dragon Skin due to its higher stiffness formed into a rainbow shape (right).

C. Dual Material Tentacle

The previous design shows that an off-axis air channel with pure Ecoflex results in desirable twisting behavior. However, due to Ecoflex's high flexibility, the tentacle does not retain its curling shape easily under external forces. Our exploration of dual material strategies was driven by the goal of creating a stiffer tentacle by varying the material composition to support a wider range of load applications.

1) Longitudinal Segmentation Method: A combination of Ecoflex and Dragon Skin was explored to leverage the distinct properties of both materials. To demonstrate that curling behavior can be mechanically programmed by strategically combining materials with different properties, the tentacles manufactured in this section have homogeneous wall thickness and central air channel. Configurations with Dragon Skin positioned centrally and Ecoflex on the sides, as well as the reverse arrangement, were tested. When Dragon Skin was placed in the center, it restricted uniform expansion, leading to bending from the stiffer core. Conversely, positioning Dragon Skin on the sides effectively limited the expansion of Ecoflex, resulting in a curling effect. The results are shown in Fig. 5.

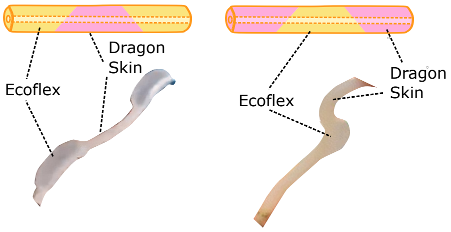

Fig. 5. Design and inflation results of the tentacle with longitudinal material segments center air channel. The Ecoflex sections expand and the Dragon Skin sections restrict expansion. The angled arrangement of the two materials causes the regions with more Ecoflex to stretch further, leading to a curvature during inflation.

2) Transversal Segmentation Method: The dual material experiments demonstrated that Ecoflex expands while Dragon Skin limits the expansion under the same air pressure. Thus, placing Dragon Skin and Ecoflex along the longitudinal axis should further enhance curling behavior, complementing the effect of eccentric wall thickness. Additionally, a higher ratio of stiffer material enhances the tentacle's strength. Accordingly, Ecoflex and Dragon Skin were filled into a mold of 11 mm diameter and 20 cm length, parallel to the longitudinal axis, with varying ratios as shown in Fig. 6, with an off-axial air channel. As the proportion of Ecoflex increases, the tentacle achieves greater curvature during inflation. This is because Ecoflex, being softer, expands more readily under air pressure, while the stiffer Dragon Skin resists expansion. The imbalance in flexibility between the materials causes the tentacle to bend more where Ecoflex dominates. In the 70% Dragon Skin configuration, the air channel is fully surrounded by the stiffer material, preventing sufficient inflation and resulting in limited deformation. As such, this setup does not significantly contribute to the investigation.

For the manufacturing, molds were cut for 30%, 50%, and 70% volumes of the full mold, filled with one material, allowed to cure, then placed into the full mold and fixed. The remaining volume was filled with the other material. The workflow is described in Figure 7.

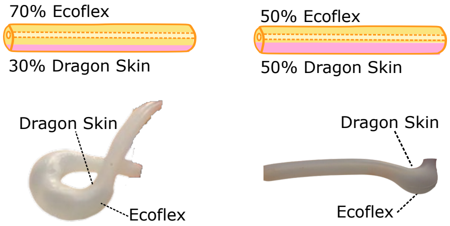

Fig. 6. Tentacles with dual-material distribution along the transverse axis and off-axis air channels. As the proportion of Ecoflex increases, greater curvature is achieved upon inflation under the same air pressure.

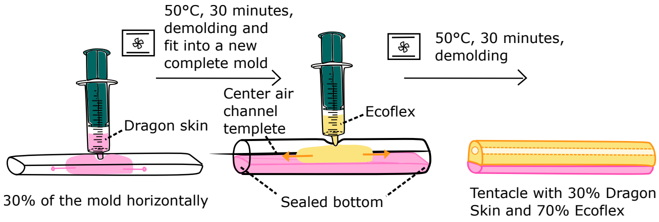

Fig. 7. Fabrication process of a dual material soft robotic tentacle with off-axis air channel. Initial casting of Dragon Skin silicone (30% by volume) in a semi-cylindrical mold. Transfer of cured Dragon Skin component to a full cylindrical mold. Injection of Ecoflex (70% by volume) using a syringe to complete the tentacle structure. Final dual-material tentacle with Dragon Skin base (pink) and Ecoflex top layer (yellow).

The two materials generally cure well together and adhere effectively though with a visible separation line as shown in Fig. 8. No separation was observed during trials.

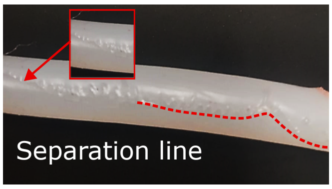

Fig. 8. Separation line between Dragon Skin and Ecoflex

3) 45° Iterative Segmentation Method: After examining the interaction of Ecoflex and Dragon Skin in the previous experiments, it was inferred that filling the mold with Ecoflex and Dragon Skin at a 45-degree angle would induce a curling effect in the tentacle due to the interaction between the two materials during inflation. Additionally, it was expected that the position of the air channel, whether centered or off-centered, would affect the degree and nature of the curling behavior.

To test this hypothesis, the mold was filled iteratively with Ecoflex and Dragon Skin at a 45-degree angle as shown in Fig. 9. The process began by positioning the mold at a 45-degree angle and filling it with Ecoflex. After curing, the mold was rotated 180 degrees along its longitudinal axis and secured, followed by the addition of Dragon Skin. This alternating filling and curing process was repeated until the mold was fully filled. The pneumeatics channel was positioned in both centered and off-centered configurations to evaluate its effect on the curling behavior.

As hypothesized, the tentacle exhibited distinct curling behavior, with the inflated Ecoflex layer exerting pressure on the Dragon Skin, causing curvature to form. In this case, Dragon Skin areas acted as pivot points, allowing the tentacle to bend as Ecoflex expanded. The position of the air channel further influenced the results, with the off-centered configuration producing a more pronounced curl compared to the centered setup as shown in Fig. 10. This confirms the critical role of both the air channel placement and the interaction between Ecoflex and Dragon Skin in determining the degree of the curling behavior.

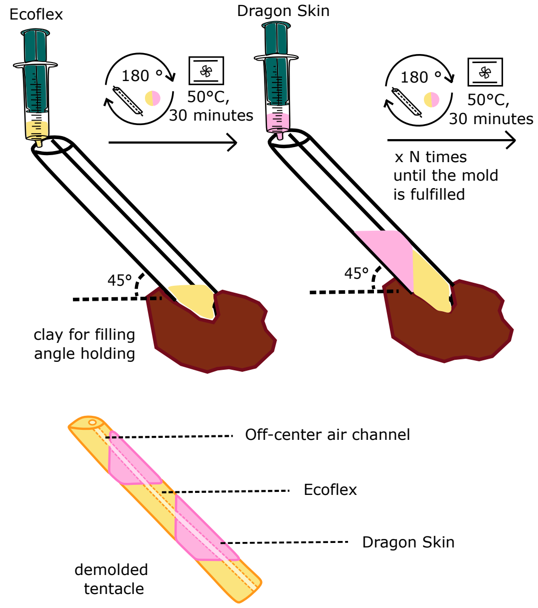

Fig. 9. Fabrication of 45-degree iteratively filled dual materials tentacle. The mold, positioned at 45 degrees, is partially filled with Ecoflex, cured, and then rotated 180 degrees longitudinally for Dragon Skin addition. This process is repeated until the mold is filled, creating a tentacle with alternating Ecoflex and Dragon Skin layers.

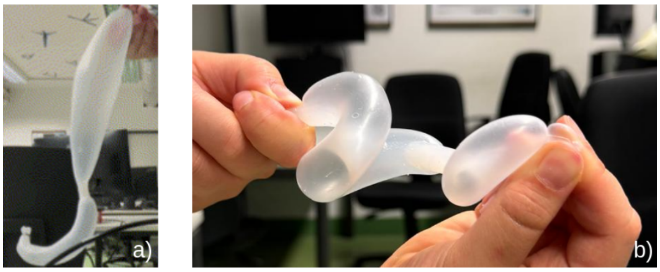

Fig. 10. Tentacle with 45-degree iterative filling method, air channel in-center (a) and air channel off-center (b)

III. RESULTS

This section outlines the evaluation of the manufactured soft tentacles in terms of their ability to grasp and lift objects, focusing particularly on the pull-off force required for the tentacle to release the object. To assess performance, we used a pneumatic system to inflate the tentacles until they were fully wrapped around the objects. A force gauge was employed to record the pull-off force. The key variable in these tests was the position of the object relative to the tentacle prior to inflation. This general approach allowed us to determine how effectively the tentacles could adapt to and manipulate the objects, as illustrated in Fig. 11.

- **Grasping Method A**: In this approach, the object—a force gauge—was placed adjacent to the tentacle in its deflated state. Upon inflation, the tentacle wrapped around the body of the force gauge, gripping it securely. The pull-off force was then measured by pulling the force gauge away from the tentacle.

TABLE II

COMPARATIVE ANALYSIS OF FAILURE FORCE AND DIFFERENTIAL PRESSURE FOR DIFFERENT TENTACLE CONFIGURATIONS

	Grasping Method A		Grasping Method B		Grasping Method C	
Tentacle Type	Failure Force	Differential Pressure	Failure Force	Differential Pressure	Failure Force	Differential Pressure
2 x 100% Ecoflex off-centered	–	–	$\geq$ 5N	191 × 2kPa	–	–
100% Ecoflex	3.5N	173kPa	2N	173kPa	$\geq$ 12N	231kPa
70% Ecoflex 30% Dragon Skin	1.5N	178kPa	2.5N	192kPa	$\geq$ 30N	311kPa
50% Ecoflex 50% Dragon Skin	3N	352kPa	2N	352kPa	$\geq$ 50N	338kPa
45° segmentation	2N	246kPa	3N	270kPa	$\geq$ 38N	314kPa

- **Grasping Method B**: The tentacle was inserted into the handle of the force gauge in its deflated state. Upon inflation, the tentacle expanded within the handle, gripping the object from the hole.
- **Grasping Method C**: The tentacle was placed inside an empty water bottle in its deflated state. During inflation, the tentacle conformed to the inner walls and secured around the opening of the bottle. After inflation, the force gauge was attached to the bottom of the bottle to measure the force required to dislodge the tentacle from the bottle.

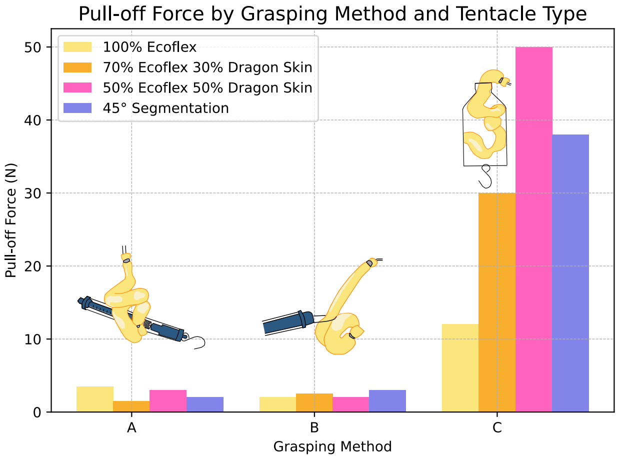

Fig. 11. Relationship of the tentacle stiffness and the pull-off force

In all strategies, the tentacle's inflation caused it to take on a specific shape and exert pressure on the object. The force required to dislodge or release the object (referred to as pull-off force) was then measured using the force gauge. Each experiment was conducted with four tentacles that demonstrated optimal curling behavior, and the results of the tests are presented in Table II.

The relationship between the material stiffness and the pull-off force is illustrated in Fig. 11. In the graph, pinker shades represent a higher concentration of Dragon Skin, indicating increased stiffness in the tentacles. And more yellow shades represent the higher concentration of Ecoflex.

The results show that in strategies A and B, all four tentacles exhibited similar behavior, with surface friction acting as the primary force securing the object. For Strategy A, we tested the use of two 100% Ecoflex tentacles, leveraging the potential for multiple tentacle application. However, this configuration led to mutual interference between the tentacles, hindering the establishment of a stable grip on the object. In Method B and C, the use of two 100% Ecoflex tentacles was omitted, as their dimensions were incompatible with the gauge's and bottle's opening.

However, in grasping method C, a clear correlation was observed between the stiffness of the material and the force it could withstand. The stiffer the tentacle, the greater the force required to deform and extract it from the bottle under shear stress. Furthermore, grasping method C exhibited a higher force threshold compared to strategies A and B. This can be explained by the combined effects of friction, geometrical interlocking and the additional force needed to ”squeeze” the tentacle through the opening of the bottle, increasing its resistance. By contrast, in strategies A and B, the tentacles first untangled before releasing the object, a behavior not observed in method C, where the tentacle maintained a firm grip throughout the experiment 12.

It is worth noting that in strategy C, the 45-degree segmented tentacle performs well, even though only the Ecoflex section inflates and contacts the bottle. Intuitively, it should behave similarly to the 100% Ecoflex tentacle. However, the key difference lies in deformation distribution: in the 100% Ecoflex tentacle, applied force causes deformation along the entire length due to the material's continuity, reducing the overall contact area with the bottle. In contrast, the 45-degree segmented tentacle, with Dragon Skin sections in between, prevents deformation from propagating through the entire structure. This allows the remaining Ecoflex segments to retain their shape, ensuring better contact and a more secure grip.

In addition to these observations, the tentacles are shown to be especially effective at manipulating objects with complex topologies or intricate geometries, such as those with holes or voids, where the tentacles can conform to the object's shape, highlighting their versatility in handling complex and irregular geometries.

IV. CONCLUSION

This paper investigated the effects of different material ratios and geometrical distributions in pneumatic soft actuators

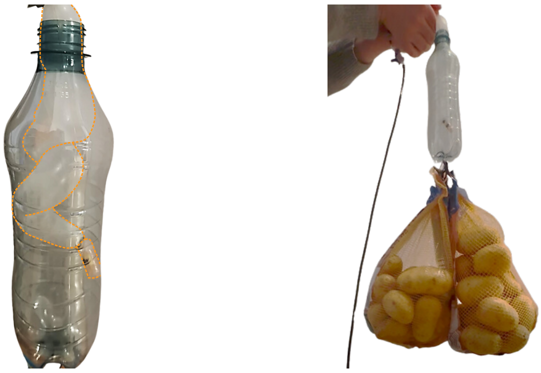

Fig. 12. Grasping method C with a 50% Ecoflex and 50% Dragon Skin tentacle. The tentacle is placed inside a bottle to test its gripping and load-bearing capabilities. (Left) When inflated to a differential pressure of 338 kPa, the tentacle curls, creating multiple contact points with the neck and inner surface of the bottle. (Right) The tentacle grips the bottle from the inside, holding a 5 kg load while the experimenter lifts only the tentacle.

to enhance the 3D deformation capabilities and load-bearing capacity of soft robotic tentacles. By employing seven distinct filling strategies, it was demonstrated that the internal geometrical distribution of dual-material elastomers with varying stiffness significantly influences the tentacle's performance. Tentacles composed of pure Ecoflex were effective for gently grasping delicate objects but lacked sufficient strength for heavier loads. The integration of stiffer materials, such as Dragon Skin, addressed this limitation. Specifically, a combination of 50% Ecoflex and 50% Dragon Skin using a transversal segmentation filling method achieved the highest load capacity, reliably supporting forces exceeding 50 N. These results confirm the initial objectives outlined in the introduction, validating that strategic material composition and spatial arrangement can enhance complex 3D movements and significantly improve load-bearing capabilities in soft actuators.

Future work will address fabrication challenges, including air bubble elimination, improved demolding techniques, and tear prevention, to enhance the structural quality of the tentacles. We will explore smaller diameters and longer lengths to facilitate better entanglement and improve collective grasping capabilities. Specific focus will be placed on refining grasping Method A to optimize its performance. Additionally, evaluating fatigue resistance under repeated loading and inflation cycles will provide critical insights into long-term durability, contributing to the development of more robust soft robotic systems. Defining more uniform performance metrics will enable consistent evaluation and comparison. Furthermore, integrating soft tentacles with rigid robotic systems is anticipated to expand their applications by combining the benefits of flexibility with precision.

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