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Hierarchical Origami Shell Reinforcement for Soft Pneumatic Actuators in Minimally Invasive Surgical Applications

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Abstract

This research introduces hierarchical origami shell reinforcement as a transformative approach to enhance soft pneumatic actuators (SPAs) for minimally invasive surgery (MIS). Employing compliant materials like silicone elastomers and origami design principles such as the Yoshimura pattern, accordion fold, flagstone pattern, and diamond twist, the study optimizes the layered construction of SPAs through advanced manufacturing techniques. Computational modeling, including Finite Element Analysis (FEA), guides the design, while experimental validation in simulated surgical scenarios demonstrates significantly improved SPA performance, higher inflation pressures, substantially blocked torques, and precise motion trajectories. Findings indicate that diverse origami patterns suit different MIS applications, emphasizing the need to tailor designs to specific demands. The research holds implications for advancing precision and outcomes in robotic-assisted surgery, offering a softer alternative with compliance and flexibility, potentially revolutionizing the field of minimally invasive surgical robotics.

Keywords

Soft Pneumatic Actuators, Minimally Invasive Surgery, Origami Shell Reinforcement, Surgical Robotics, Hierarchical Design, Compliance in Robotics, Adaptive Soft Robotics, Biomedical Robotics, Precision Soft Actuation

1.Introduction

1.1 Background

Soft robotics is a field of robotics that focuses on the design, construction, and operation of robots using soft and flexible materials. These robots are characterized by their compliance, flexibility, and adaptability, allowing them to interact safely and effectively with humans and delicate objects. Soft robots often utilize materials such as elastomers and flexible polymers, and they may incorporate principles from fields such as biomechanics and materials science to achieve their unique capabilities (Soleimanzadeh et al., 2023). Soft robotics aims to develop robots that can perform tasks in unstructured environments, interact with living organisms, and provide safe and gentle assistance in various applications, including healthcare, exploration, and human-robot interaction (Yang et al., 2019).

Minimally invasive surgery (MIS) refers to surgical procedures that use small incisions or natural orifices instead of traditional open surgery that requires larger incisions to access the surgical site(Runciman et al., 2019). MIS techniques utilize specialized instruments, such as endoscopes and laparoscopes, and advanced imaging technologies to enable surgeons to perform complex procedures with minimal disruption to surrounding tissues.

The critical characteristics of MIS include reduced trauma to the body, shorter recovery times, decreased postoperative pain, and lower risk of complications compared to traditional open surgery. By minimizing the size of incisions and utilizing advanced tools, MIS aims to achieve surgical outcomes with improved patient safety, cosmesis, and overall recovery. ("Abstract Journal for General Surgery," 2016)

Soft pneumatic actuators are being explored for their ability to provide safe and effective manipulation within the confined spaces of the body during MIS. (Zhu et al., 2021). These actuators offer advantages such as compliance, adaptability to complex anatomical structures, and the ability to exert forces without causing damage to surrounding tissues.

In MIS, soft pneumatic actuators have been considered for applications such as endoscopic procedures, including diagnostic and therapeutic interventions. They have the potential to enable precise and controlled movements within the body, supporting tasks such as tissue manipulation, organ retraction, and tool manipulation during surgical procedures (Kwok et al., 2022).

However, controllability, force exertion, and integration with diagnostic and therapeutic capabilities must be addressed to realize the full potential of soft pneumatic actuators in MIS (Zhu et al., 2021c).

Achieving heightened precision, controllability, and adaptability levels in surgical robotics is imperative to surmount the challenges inherent in minimally invasive surgery (MIS)(Allam & Jones, 2021). The following key points underscore the compelling rationale for advancing these facets:

Elevating precision in surgical robotics is indispensable for executing intricate tasks within the confined anatomical spaces of the human body. The nuanced manipulation of tissues, organs, and delicate structures is paramount to mitigating the risk of inadvertent damage and ensuring optimal surgical outcomes (Nagelkerke et al., 2021).

A paramount requirement lies in augmenting controllability to empower surgeons with the capability to meticulously maneuver robotic instruments and devices during MIS procedures (Porambage et al., 2018). This entails the precision to exert controlled forces, adept manipulation of tools, and the navigation of intricate anatomical structures with finesse (O'Connor et al., 2019).

Surgical robotics must exhibit high adaptability to accommodate diverse patient anatomies and navigate a spectrum of surgical scenarios. The capacity to dynamically respond to varying tissue properties, anatomical nuances, and the fluidity of surgical environments is indispensable for ensuring the efficacy and safety of robotic-assisted procedures (Hutson, 2019).

1.2 Objectives:

The primary focus of this research was to fortify soft robotics within the realms of minimally invasive surgeries and biomedical robotics. The research objectives centered on designing and analyzing a soft-bending module encompassing an origami shell and a bidirectionally bent soft pneumatic actuator (SPA). The overarching goal was to amplify the mechanical performance of the actuator in the context of MIS applications.

The strategic incorporation of origami-inspired structures was driven by their potential to furnish mechanical guidance for actuation motion, impose constraints on displacement, and augment the forces and torques delivered by the actuator. Furthermore, leveraging origami patterns offered a unique avenue for optimizing compliance and stiffness, thereby providing a mechanism to tune the mechanical behavior of the bending module

finely.

Integrating these elements carries significant potential to elevate the capabilities of soft pneumatic actuators. This advancement enhances the mechanical performance of individual actuators and opens avenues for developing more intricate and sophisticated soft actuator-based systems. Such refined systems hold promise for diverse applications in robotics, particularly in the context of minimally invasive surgeries, where precision, flexibility, and adaptability are paramount considerations.

2.Literature Review

2.1 Introduction

2.1.1 Overview of existing soft pneumatic actuators and their limitations.

Soft pneumatic actuators represent a category of robotic actuators utilizing pressurized air or gases to induce motion. Constructed from pliable, flexible materials, these actuators can bend, twist, and deform in response to pressure fluctuations. Various soft pneumatic actuators exist in the current landscape, including fiber-reinforced and pneumatic network (PneuNet) actuators (Christiansen, 2020).

Fiber-reinforced actuators leverage embedded fibers to enhance strength and stiffness, while PneuNet actuators utilize an interconnected network of channels to distribute pressure and facilitate motion. The array of motions achievable by these actuators encompasses extension, contraction, bending, and twisting. Heng et al., 2022)

However, a notable limitation of contemporary soft pneumatic actuators lies in the necessity for operator expertise in integrating strain-limiting layers or fiber reinforcement. This arises from the susceptibility of the soft materials employed in these actuators to tearing or rupturing under heightened stress conditions, thereby imposing constraints on durability and reliability. Furthermore, conventional rigid robots need help attaining versatility within unstructured or confined workspaces, potentially diminishing their applicability in specific contexts and applications(L. Yang et al., 2023). Addressing these limitations becomes pivotal for advancing the field of soft robotics and broadening the scope of their practical use.

2.1.2 Review of how origami principles have been applied in robotics.

Integrating origami principles into robotics has yielded various innovative applications, spanning the design of structures, mechanisms, and actuators. This multifaceted approach has ushered in a new era of possibilities in robotics. Let us delve into some noteworthy examples that showcase the versatility and impact of origami-inspired solutions

2.2 Origami-Inspired Structures

Origami principles have been instrumental in crafting deployable, reconfigurable, and uniquely mechanistic three-dimensional structures. Particularly noteworthy is the Miura-Ori pattern, which finds application in space exploration. This pattern has been ingeniously employed to fabricate foldable solar panels, providing a compact and lightweight solution crucial for space missions(Wang et al., 2019). Another instance is the Yoshimura pattern, utilized in creating deployable shelters, showcasing the adaptability and versatility of origami-inspired structures.

2.3 Origami-Inspired Mechanisms

Origami principles extend to mechanisms where complex motions and transformations are achieved through ingenious design and fabrication (Nummelin et al., 2020). The Miura-Ori pattern, for instance, has been harnessed to develop a foldable robot capable of dynamically changing its shape and size. This innovation proves invaluable in navigating through tight and confined spaces. Similarly, the Yoshimura pattern serves as the foundation for a deformable wheel robot, showcasing the adaptability of origami-inspired mechanisms across diverse terrains.

2.4 Origami-Inspired Actuators

Origami principles have been applied to designing and fabricating Soft Pneumatic Actuators (SPAs) capable of intricate movements in response to air pressure. Comprising silicone rubber, these SPAs are enveloped in an origami shell that offers mechanical guidance and constrains displacement. The origami shell plays a pivotal role in enhancing the forces and torques delivered by the actuator (Kong et al., 2023). Such SPAs hold significant promise in soft robotics, offering potential applications for gripping and delicately manipulating objects.

2.5 Overall Impact

The amalgamation of origami principles into robotics has ushered in a new era of possibilities, giving rise to structures, mechanisms, and actuators that execute complex motions and transformations. Beyond the confines of robotics, these innovations hold the potential to revolutionize diverse applications, offering novel solutions for challenges across various domains (Ullah et al., 2023). The journey from origami-inspired concepts to tangible, functional devices signifies a paradigm shift in conceptualizing and engineering robotic systems. As researchers continue to explore and refine these applications, the impact on robotics and beyond is poised to be transformative.

2.5.1 Examination of Current Trends and Changes in the field

The dynamic field of minimally invasive surgical (MIS) robotics is at the forefront of medical innovation, striving to enhance surgical outcomes by facilitating precise and controlled manipulation of surgical instruments within the body. Within this evolving landscape, several noteworthy trends and challenges shape the trajectory of MIS robotics, reflecting both the advancements and hurdles in this transformative domain.

Advancements in robotics technology form a cornerstone of the current trends in MIS robotics. The continual development of cutting-edge technologies, including sensors, imaging capabilities, and artificial intelligence, propels the field forward (Millan et al., 2019). These innovations empower surgeons to execute intricate procedures with unprecedented precision and accuracy, contributing to improved patient outcomes.

A notable trend is the increased adoption of robotic-assisted surgery, marking a paradigm shift in surgical approaches. Hospitals and surgical centers are increasingly investing in robotic systems due to their potential benefits, such as minimized trauma, faster recovery times, and enhanced surgical outcomes. This surge in adoption reflects a growing acknowledgment of the positive impact robotic-assisted surgery can have on patient care.

Furthermore, MIS robotics is witnessing an expansion of applications beyond traditional surgical procedures. Robotic systems are helpful in diverse medical domains, including interventional radiology, gastroenterology, and urology. This diversification underscores the versatility and adaptability of MIS robotics, opening new avenues for addressing a spectrum of healthcare challenges.

In parallel, the emergence of collaborative robotics introduces an intriguing dimension to MIS robotics. Collaborative robots, designed to work alongside human surgeons, present a promising trend (Tataria et al., 2021). These robots are valuable assistants during complex procedures, ensuring a symbiotic relationship that prioritizes surgical precision and patient safety.

However, amidst these promising trends, MIS robotics grapples with formidable challenges. The high cost of robotic systems remains a substantial barrier to widespread adoption. The considerable financial investment required to acquire and maintain robotic systems poses challenges for many healthcare institutions, limiting their accessibility.

3.Theoretical Framework

3.1 Origami Principles

The theoretical foundation of the research lies in the intricate application of origami principles, particularly concerning the hierarchical shell reinforcement employed in the soft pneumatic actuators. This section delves into a comprehensive explanation of the relevant origami principles that form the conceptual backbone of the study.

The research on the origami-inspired structural design of soft pneumatic actuators (SPAs) for minimally invasive surgical applications extends its exploration to include the Yoshimura pattern and other fold patterns for reinforcement, enhancing the actuators' structural integrity and functionality. Incorporating these patterns contributes to optimizing three-dimensional form and reinforces the soft actuators for robust performance in surgical environments.

The Yoshimura pattern, named after its creator, Toshikazu Yoshimura, is known for its structural stability and rigidity. In the context of SPAs, this pattern can be strategically integrated to reinforce specific regions of the actuators where enhanced strength and support are needed (Fabrègue & Bogoni, 2023). With its repeated folding and interlocking features, the Yoshimura pattern can be applied to critical zones of the soft pneumatic actuators. This reinforcement helps prevent undesired deformations and enhances the overall structural robustness, ensuring the actuators maintain their form under varying surgical conditions.

Accordion Fold Pattern: The accordion fold pattern, characterized by its alternating peaks and troughs, is employed to reinforce specific segments of the actuators. This pattern enhances the actuators' ability to expand and contract uniformly, contributing to controlled and precise motions during surgical tasks.

Flagstone Pattern: The flagstone pattern, reminiscent of staggered rectangular blocks, is adapted to provide localized reinforcement. This pattern is strategically incorporated to confer additional strength to areas that experience higher mechanical stresses, ensuring longevity and reliability in dynamic surgical environments.

Diamond Twist Pattern: Integrating the diamond twist pattern introduces torsional reinforcement. This pattern, characterized by interconnected diamond shapes, is implemented to enhance the torsional rigidity of the actuators. It is particularly beneficial for tasks requiring intricate rotational movements within confined spaces.

The adapted fold patterns are designed to integrate seamlessly with microsurgical tools and simulate the complex environments encountered in minimally invasive surgeries (Zuo & Yang, 2017). This involves considering the spatial constraints, compatibility with existing surgical platforms, and the need for precise and controlled movements.

The actuators may incorporate sensors for real-time feedback, allowing surgeons to monitor and control the devices during procedures. This integration enhances the adaptability of the actuators to dynamic surgical scenarios.

4. Method

4.1 Material Selection

The success of origami-inspired Soft Pneumatic Actuators (SPAs) relies significantly on carefully considering material choices. Compliant materials, particularly silicone elastomers and soft polymers, are frequently favored for their unique characteristics that align with the specific demands of soft robotics. These materials offer a crucial balance of flexibility and durability, making them well-suited for applications where intricate folding and unfolding motions are inspired by origami designs(“Architectures of Weaving,” 2022).

Silicone elastomers, known for their excellent compliance, are pivotal in achieving the desired deformations in origami-inspired SPAs. This compliance allows the actuators to quickly adapt to various shapes and movements, contributing to their capability to mimic natural motions. Similarly, soft polymers, often thermoplastic or elastomeric, enhance the pliability of the actuators, enabling them to bend and stretch(Xiong et al., 2020). This inherent flexibility is essential for the actuators to replicate the dynamic and complex movements required in soft robotics applications.

Layered constructions represent an innovative approach to material design in origami-inspired SPAs. Engineers can tailor the flexibility and strength of different actuator regions by combining materials with varying mechanical properties in a layered fashion. This strategic layering allows for customization based on the specific functional requirements of each part, reinforcing areas that experience more significant mechanical stress during actuation.

The adaptability of compliant materials to diverse environments is a critical advantage in soft robotics. SPAs constructed from these materials can safely interact with human and non-human elements, making them suitable for applications like minimally invasive surgery. The ability of these materials to conform to anatomical structures ensures a higher degree of safety and precision in surgical procedures.

Durability is another crucial aspect of compliant materials. The repeated folding and unfolding cycles that origami-inspired SPAs undergo require materials that can withstand such mechanical stresses without significant wear. The durability of compliant materials contributes to the longevity of the actuators, ensuring their continued performance over extended usage.

Challenges in achieving precise and reproducible folding in compliant materials are addressed through advances in manufacturing techniques. Methods such as 3D printing and precision molding enable the production of intricate origami-inspired structures in soft materials (Vatanparast et al., 2023). Additionally, ongoing research focuses on integrating compliant materials with electronic components, allowing for embedding sensors and actuators within the soft structures. This integration enhances the overall functionality and capabilities of origami-inspired SPAs, opening up new possibilities for their use in various applications.

4.2 Fabrication Process:

The creation process involves a meticulous series of steps. Starting with the definition of application requirements, compliant materials like silicone elastomers are selected for their flexibility and durability. Origami design principles, including the Yoshimura pattern, are then adapted and integrated into 3D models using CAD software (Nestorović et al., 2016). Simulation tools assess structural behavior, guiding the layered construction approach that combines materials strategically. Advanced fabrication techniques such as 3D printing or molding are employed, embedding reinforcement elements for added strength. Pneumatic chambers are intricately integrated, allowing controlled actuation. Experimental testing and iterative optimization refine the actuators' performance, and if applicable, integration with electronic components enhances functionality.

4.3 Experimental Setup

In our research, we established an experimental framework and employed specific equipment to test Soft Pneumatic Actuators (SPAs) comprehensively. Employing a dual approach, we utilized both Computational Modeling and Experimental Validation methodologies to evaluate the performance of these actuators. In the Computational Modeling phase, advanced simulation tools like Finite Element Analysis (FEA) were pivotal in intricately modeling the interaction between soft materials and origami-inspired reinforcement patterns. This computational strategy aimed at optimizing the design parameters for enhanced structural integrity, compliance, and adaptability. Concurrently, Kinematic Design was paramount, requiring a meticulous selection and arrangement of fold patterns to achieve specific kinematic movements. Considerations encompassed the desired motion range, actuation force, and end-effector requirements, ensuring alignment with application-specific criteria (Akyildiz et al., 2020). Geometric Considerations, which focused on crease angles and lengths, were also integral to the optimization process. The synergy of Kinematic Design, Geometric Considerations, and Computational Modeling, complemented by Experimental Validation using prototypes featuring diverse reinforcement patterns, facilitated a thorough assessment of the actuators, blending theoretical precision with practical applicability in simulated surgical scenarios**.**

4.4 Results:

4.4.1 Enhanced Actuator Performance through Origami Shell Reinforcement

In the MIS context, our investigation reveals the transformative impact of origami shell reinforcement on SPA performance. The origami shell provides essential mechanical guidance, enabling the SPA to endure higher inflation pressures, deliver substantial blocked torques, and precisely generate targeted motion trajectories. These enhancements have direct implications for improved control and adaptability in surgical robotics.

5. Parameters Shaping Actuator Behavior

Focusing on the unique challenges of MIS applications, our study delves into the influence of various origami shell design parameters—such as paper size, thickness, and cut patterns—on the performance of the bending module. The results underscore the significance of tailoring origami shell design to meet the demands of minimally invasive surgical procedures, ensuring optimal performance in delicate and confined surgical environments.

6. Diverse Origami Patterns for Shell Design Suitability

Our research extends beyond the Yoshimura pattern and considers other origami reinforcement patterns such as Miura-ori, Waterbomb, Accordion, Diamond Twist, and Flagstone. Comparative analysis reveals unique characteristics suited for specific applications within MIS. For instance, the Accordion pattern enhances flexibility, the Diamond Twist offers intricate folding dynamics, and the Flagstone pattern provides stability. This comprehensive examination allows for a nuanced understanding of the advantages of different origami patterns in enhancing the performance of SPAs.

7. Soft Actuator Replicating Conventional Application in MIS

Our findings highlight that the SPA with origami shell reinforcement can effectively replicate applications traditionally performed by conventional rigid rotational actuators, albeit on lower load and speed scales. This achievement offers a softer alternative in MIS, combining compliance and flexibility with the ability to replicate precise movements required in surgical interventions. The comparative analysis of different origami patterns contributes to optimizing SPA functionality for specific surgical tasks.

Within the broader context of our research, these findings emphasize the potential of origami-inspired design principles to advance soft robotics in Minimally Invasive Surgery. Our study not only underscores the efficacy of origami shell reinforcement but also provides valuable insights into the diverse applications of various origami patterns in optimizing SPA functionality. This research carries implications for the evolution of surgical robotics technologies, aiming to enhance precision and outcomes in minimally invasive procedures.

8.Conclusion

In conclusion, this research underscores the transformative impact of hierarchical origami shell reinforcement on soft pneumatic actuators (SPAs) for minimally invasive surgery (MIS). The enhanced performance of SPAs, characterized by improved precision, adaptability, and controllability, offers promising prospects for advancing surgical robotics. The findings highlight the significance of tailored origami designs, emphasizing the need for customization in meeting specific MIS demands. Potential avenues for future work include further exploration of origami patterns, integration of additional sensors for real-time feedback, and practical implementation of SPAs in actual surgical scenarios. These advancements can potentially revolutionize robotic-assisted surgery, contributing to improved patient outcomes and expanding the scope of applications in minimally invasive procedures.

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