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Comparative Study of Internal Structural Geometry and Material Properties on Soft Gripper Performance

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Abstract
Soft grippers signify an important development in soft robotics, granting the ability to safely, effectively, and efficiently manipulate sensitive, nonlinear, or variable-sized objects across many applications from healthcare, food processing, logistics, and human robot collaboration. The two main aspects of any soft gripper's performance are due to fundamental design properties: internal structural geometry and material properties. Not only have previous studies typically assessed these variables in isolation, but there are also few experimental studies assessing their interplay. We present comparative experiments to evaluate the effects of internal geometrical design structures on the performance of 3D-printed TPU soft grippers a highly elastic and durable thermoplastic elastomer, compatible with typical FDM printing processes. Three distinct internal geometries circular, linear, and zigzag were designed and 3D-printed to assess the effects of geometrical design on performance measures like grip force, deformation, adaptability, slip resistance, and durability. The grippers were integrated with a servo-driven gear-synchronized actuation mechanism and performance testing was conducted using force-sensitive resistors (FSRs) to evaluate gripping interaction forces. Experimental results reveal that the linear geometry achieves the highest grip force and slip resistance, the circular geometry provides the greatest adaptability and deformation range, and the zigzag geometry offers a balanced compromise between strength and flexibility with superior long-term durability. These findings highlight the trade-offs between stiffness and compliance inherent in internal geometrical design and emphasize the necessity of jointly considering material properties and geometry when developing application-specific soft grippers.

1. Introduction

Soft robotics is a nascent area that takes inspiration from biology to form machines that are flexible, adaptable, and able to interact safely with their envir onment. Whereas traditional rigid robots have hard joints and actuators, soft robots are usually made (and actuated) from compliant materials—including many types of silicones, elastomers, and polymers. This flexibility allows soft robots to deform, conform, and adapt their shape when interacting with objects. Thus, soft robots can operate without requiring their operational safety to be painstakingly specified in advance [8].

Soft grippers within soft robotics are also one of the most common, researched, and used technologies. They address a fundamental limitation of rigid robotic grippers that use hard rigid frames for grasping and manipulating objects of large size variations—so objects that are delicate, irregular in shape, or the size highly variable. Conventional grippers often use exact position sensing at all times and need good control algorithms with additional sensor feedback to deal with variability and secure the grasp. Soft grippers can enable a secure grasp on objects through some other passive compliance and adaptability in material. It is also possible for a soft gripper to perform a successful grasping on a greater number of objects with little to no pre-programming using the flexibility and deformability of the material of the hand [1].

Soft grippers have great significance across a variety of application domains. In healthcare they enable minimally invasive surgical tools, and safe (and capable) assistive devices that in turn can interact with human tissue [11]. In food processing and agriculture applications they can harvest soft or otherwise delicate produce like fruit and vegetables while avoiding damaging the fruit or produce, —a challenge which is particularly difficult for rigid systems [5]. In industrial and logistics applications soft grippers can grasp objects of unknown shapes and orientations, which increases the efficiency and versatility of automation systems. In human-robot interaction scenarios soft grippers ensure safety against injury, a key consideration for collaborative robots (and cobots) that are typically co-located with people. Overall soft grippers combine elements of adaptability, safety, and versatility, marking soft robotics' promise of achieving functionality beyond rigid systems. However, an application specific performance of a soft gripper is directly related to design and material choices of soft robots which influence functionality in achieving robustness, efficiency, and reliability [6].

A soft gripper's performance is solely influenced by two fundamental design characteristics: internal structural geometries and materials. The internal geometry, or more specifically, how the actuating chambers are arranged and shaped, is one of the most fundamental factors that determines how a soft gripper changes shape when actuated. By changing the internal design of a soft gripper, such as whether it has cylindrical, conical, or multi-segmented chambers, the bending angle, range of motion, and the way in which forces are distributed in the actuation phase when grasping will change [4]. Similarly, there are other factors related to geometry, like wall thickness, distance between the chambers, and reinforcements (e.g., fiber reinforcement, anisotropic layered reinforcement) that will affect soft gripper performance. For instance, a gripper can have maximum deformation and flexibility with thin walls, but the lack of structural stability makes it impractical for applications. On the other hand, reinforced geometries can offer directional stiffness, increasing precision/coordination and grip strength. Ultimately, the geometry must define how adaptable the gripper is to hold any given object securely, given it can range from small to large, and from symmetrical to irregularly shaped. In conjunction with the geometry are material properties. The intrinsic properties of the material itself will have a direct impact on how stiff or compliant a gripper is capable of being. The elastic range of materials, along with stiffness, will ultimately decide the additive mechanical advantage given both flexibility and strength. Generally, allowing materials with greater elastic range to be relatively compliant can also allow for complete adaptability to irregular shapes for example, however, the same material may not be capable of removing heavier prey [3].

Stiffer materials can generate higher gripping forces, although they typically sacrifice flexibility. Furthermore, durability and fatigue resistance are also important factors, as soft grippers usually undergo repeated deformation cycles in real-world use. Moreover, gripper performance will depend on surface-related properties, such as friction coefficients, which affect the gripper's ability to limit slip during grasp or handling when interacting with smooth and/or fragile objects. Due to all of these aspects, selecting the right materials is critical because it relates directly to the gripper development's mechanical performance as well as its durability and reliability [2].

While both geometry and material properties have been studied thoroughly on their own, there is limited comparative research that systematically studies material and geometric properties simultaneously. Research often focuses on optimizing structural design parameters while maintaining the same material properties or investigating the effects of varying materials with the same gripper geometry. Therefore, our understanding of how geometry and materials characteristics interact, and how their trade-offs affect gripper performance is still limited. Moving towards understanding the interplay between material characteristics and geometry is needed to develop more efficient, adaptable, and application-specific soft grippers because the optimal design is less likely to be optimized solely based on one factor, but rather carefully balancing structural and material aspects [7].

The primary objective of this research is to systematically compare the influence of internal geometrical structures and material properties on the performance of soft grippers. By analyzing both factors under controlled conditions, this study seeks to identify how they individually and collectively impact key performance metrics, including grip force, range of motion, energy efficiency, adaptability to object shapes, and long-term durability. Rather than focusing on optimizing a single design parameter, the research emphasizes the interplay between structural geometry and material characteristics, aiming to uncover the trade-offs and synergies that shape overall gripper performance [10].

2. Literature Review

Zaidi, S., et al. [9] tackled the issue of actuation technologies found in soft robotic grippers and manipulators, which represents a considerable drawback of traditional rigid robotics that struggles to interact delicately and adapt. The purpose of this paper was to provide a concise reference regarding possible forms of actuation, associating them with a specific application for the most beneficial use. The authors went on to categorize actuation technologies into six distinct types: pneumatic, vacuum, cable-driven, shape memory alloys (SMAs), electroactive polymers (EAPs), and electro-adhesion (EA). Each actuation method was considered regarding their operational principles, performance, advantages, and drawbacks. The authors found that pneumatic, vacuum, and cable-driven actuations were the most used with more active applications and reported advantages of relatively high grasping forces, control, and reliability, although they all had issues with leakage and miniaturization. On the other hand, SMAs, EAPs, and EA are emerging technologies that offer advantages such as operating quietly, having a high force-to-weight ratio, and ability to conform to the shapes of the grasped objects despite listed drawbacks, such as slow response, low force output, and sensitivity to environmental factors.The review draws attention to a research gap due to the fact that most of the applications were limited to the exclusion of applications such as pick-and-place tasks that remained limited to laboratory testing. The authors stressed the need for continued development of the emerging technologies and, preferably, their integration into established systems to facilitate effective and efficient application within the industrial environment.

In their study Zhu, J., & Hao, G. [12] described the design, modeling, fabrication, and testing of a compact monolithic compliant gripper developed for micro-manipulation. The authors were responding to challenges in complying with gripper design. Many of the issues stemmed from parasitic motion that comes from multiple degrees-of-freedom of motion presented with a parallelogram mechanism and flexure hinges including flexible cantilever beams with variable stiffness in their design. They outlined a new simple compact design with large jaw displacement motion that performed only straight parallel motion, leading to a simple design. Their approach used an integrated design concept that combined theoretical design, analytical modeling, finite element analysis (FEA), and experimental testing. The new parallel jaw mechanism represented a combination of the Scott-Russell and the parallelogram mechanisms with obstacles. The authors created a method of using a Right-Circular Corner-Filleted (RCCF) flexure hinge for larger displacement, then used a pseudo-rigid-body model (PRBM) to make analytical predictions that were backed up with FEA results and physical testing on their fabricated prototype. The testing results of the prototype performed well and achieved a near straight-line parallel jaw motion with very limited parasitic motion effects. The major take-aways from this performance were the 2.95 displacement amplification ratio, a grasping of 0.9 mm position of travel per jaw, and a safety factor of 1.4 and the stress levels at no more than 243.2 MPa. The study identified additional research gaps and areas for basic future research including: designing the compliant gripper smaller, modeling it in a non-linear context, using newer actuators for improved performance, and using new sensors for increased high-resolution accuracy.

In their work, Liu, Chung, et al. [13] presented a motor-driven, three-fingered soft robotic gripper capable of adaptive grasping for fragile objects and objects of various sizes. They aimed to improve existing designs by minimizing stress on the fingers while reducing driving force while being geometrically efficient. Research and development were carried out on the design of the compliant fingers using topology optimization and finite element modeling to evaluate the stress, input force, and displacement. The prototype was fabricated using 3D printing with thermoplastic elastomer (TPE) and was validated with experimental testing in order to ensure that the simulation measured valid metrics. Overall, the results suggested that the gripper was able to successfully grasp fragile objects, ranging from eggs to fruits to glass, as well as handle objects with a payload of up to 4.2 kg with a sizing of up to 140mm, while weighing just 1.2 kg total. The final design used less driving force and less stress than earlier versions. By applying anti-slip foam tape, payload weight increased up to 9.5 kg, proving the importance of friction for increasing load or capacity. The research has addressed the limitations of traditional soft pneumatic grippers with a low payload and inability to handle variable sizes of fragile objects. This validated design was a progression from the existing designs in soft grippers as it gave a way to use adaptive grasping with stress-minimized grasping capabilities.

Samadikhoshkho et al. [14] provided a review on classifications of robotic grippers based upon application, design specifications, and manipulative capabilities. The intention was to compress the classification of grippers for engineers, as an engineering decision based upon the classification and selection of a gripper could ultimately impact performance. A literature review was initiated, with classifications suggested that are ultimately categorized into five groups: configuration (two-finger, three-finger, flexible, multi-finger, grain-filled, bellows, O-ring), actuation (cable-driven, vacuum, pneumatic, hydraulic, servo-electric), application (surgical, assistive, industrial, underwater), size (miniature, small, medium, large), and stiffness (soft versus rigid). The results indicated that two-finger grippers were widely accepted in industry largely due to simplicity and cost, with three-finger and multi-finger grippers typically revealing greater positioning accuracy and adaptability to varying geometry and application. Flexible and grain-filled grippers are used for manipulating irregular shape/style and poor quality parts. Actuation types had unique advantages, with hydraulic providing high strength, while servo-electric grippers offered transformational flexibility. Size impacts gripper positioning precision and abilities, while stiffness impacts adaptability of the system. Soft grippers performed across a wider interface, with little precision when handling various objects. Issues with existing coverage were recognized, as few complete reviews featured all grippers; previous reviews were specialized for grippers. This review offered a classifying framework for grippers that could be beneficial to engineers and researchers alike.

Tawk, C., Gillett, A., et al. [15] introduced a 3D-printed omni-purpose soft gripper (OPSOG) designed to grasp objects of varying shapes, sizes, textures, and stiffness. The goal of the study was to design and characterize a cost-effective, multimodal operation gripper driven by soft vacuum actuation, designed to demonstrate its versatility and dexterity. Methodology involved the design of the OPSOG making tendon-driven soft fingers and a suction cup that can operate independently or together. The parts were made using fused deposition modeling (FDM) 3D printing. The design incorporated Linear Soft Vacuum Actuators (LSOVA) to produce actuation forces in the fingers; their performance was tested using blocked force, rise time, bandwidth, and lifetime. Both analytical and finite element models predicted the performance of the actuators. The gripper was placed onto a 6-DOF manipulator arm that was controlled wirelessly with a video game controller to carry out pick and place operations. The blocked force of a single LSOVA was 30.35 N, a rise time of 94 ms, bandwidth of 2.81 Hz, and lifetime of 26120 cycles were achieved, and the OPSOG managed to grasp more than 20 objects with a maximum payload to weight ratio of 7.06 and repeatable grip forces, although a research gap was indicated with no autonomous feedback control or object recognition features existing. The proposed work in the future would include incorporating cameras, machine learning, and improving the force transmission model for better autonomy and accuracy.

Park, W., Seo, S., & Bae, J. [16] presented a new hybrid gripper that combined soft and rigid materials to surpass the impediments of conventional soft pneumatic actuators (SPAs) regarding fingertip force and actuation speed. The goal was to improve both variables at the same time since previous SPAs generally improved one variable at the expense of the other. The researchers implemented three main design principles, which were to allow for a higher number of rigid structures to allow for more bending, utilize a concave space for the chamber and material for greater longitudinal strain, and create rounded edges at the transition spaces between soft and relatively rigid material to improve fingertip force. Finite Element Method (FEM) simulations were conducted, showing the design principles still had responsiveness under differing pressures. The hybrid PneuNet was built and, based on the improved features, experimentally compared in terms of fingertip force and actuation speed to traditional SPAs. The findings showed that the hybrid gripper produced 1.5–2 times more fingertip force and 1.3 times faster actuation speed than conventional SPAs. The developed hybrid gripper could grasp a range of objects, even heavier ones, without sophisticated control systems indicating potential teleoperation capabilities. This study directly tackled a significant research gap as few studies had thoroughly researched improving fingertip force and actuation speed of soft grippers as an entire system, providing a real-world advancement in robotic gripping technology.

Shintake, J., et al. [17] provided a comprehensive overview of soft robotic grippers focusing on the material sets, physical principles, and device architectures of soft grippers. It was expected that categorizing soft gripping into actuation, controlled stiffness, and controlled adhesion technologies, while tracing their paths through history and commercialization, would be the underlying aim. Consequently, a literature review was performed on the different materials bases and physical mechanism of soft gripper technologies, listing all components and classifying them into three categories based on whether they were actuation-based designs that bend elements around objects, controlled stiffness designs that took advantage of changes in rigid state, and controlled adhesion designs based on gripping by surface forces. Data showed that soft grippers generally could grasp a greater range of objects (due to compliance and flexibility). Soft grippers operated with a form of morphological computation by reducing the complexity of the controlling function with respect to the material softness. Improvements in materials - soft elastomer, shape memory alloy, and active polymers - permitted lighter devices with greater degrees of freedom, stress sensors, and stretchable distributed sensors were found to enhance the nature of object interaction. At the end of the study, there were many seeming research gaps concerning miniaturization, robustness, speed of actuation, and ability to combine sensing with control. It was stated that ultimately attempts to advance hybrid robotic gripper technology would require materials to improve processing, methods to enhance materials, and either improved solution to the integration of sensors with maximized effectiveness to assist applications to be practical.

Zhang, H., et al. [18] aimed to create a systematic design process for soft grippers that are pneumatically actuated to limit the design from being driven by intuition and biomimicry. The study defined the problem of designing a soft gripper with a topology optimization framework that posed the gripper design as a topology optimization problem employing the Solid Isotropic Material with Penalization (SIMP) method. The finger of the gripper was quantified as a cantilevered beam to maximize bending deformation, and the optimal design was fabricated with PolyJet 3D printing. The experimental validation measured the free travel trajectory and the blocked force. The findings demonstrated the optimal soft gripper finger was able to bend into a free bending path of 41° and achieve a 0.68N blocked force at an actuation pressure of 0.11MPa. The finger design exhibited pseudo-joint features similar to that of human fingers, and the results of the FEM simulation were within 2% of the experimental results. The study highlighted a number of limitations of the optimization model that included the assumption of a homogenous material, that geometric nonlinearity is ignored at high-pressure actuations, and the fact that rupture behavior of the material was ignored. Furthermore, PolyJet material had a low rupture strain which further limited the durability. Future work was suggested to address these considerations by employing flexible FDM printing and adding compressive soft sensors for closed loop control.

Tai, K., et al. [19] provided a broad-ranging overview of contemporary gripper technologies relating to the handling of deformable, fragile, and biological objects and to identify trends, innovations, and challenges. The methodology consisted of a systematic literature review that synthesized academia, industry, and case studies. Grippers were classified by application (i.e. industrial, medical, fragile object manipulation; micro/nano), material, and mechanism (i.e. impactive, astrictive, ingressive, contigutive), and comparison of design approaches were presented. The findings did reveal that modern grippers had become stronger, more adaptive, and able to perform complex manipulations. The incorporation of advanced materials (i.e. piezoelectrics, shape-memory alloys, smart fluids) increased overall performance and the use of soft robotic grippers, adaptive mechanisms, and sensor integration expanded robotic applications within surgery (i.e. a gripper with a lot of dexterity could at least theoretically allow for complicated procedures to occur without the risks associated with human factors) and delicate handling. However, the findings also indicated a trade-off that emerged from the current study of rigid grippers whereby the flexibility of the grippers in angiography applications tended to come at the expense of performance and robustness (i.e. failure). The most significant research gap identified was the lack of grippers achieving a reasonable balance among the following features: a high level of adaptability exhibited by the grippers; a high level of endurance and durability; an adequate level of precision force control; and replicable performance across different environments. The study also concludes that further research is needed to create grippers that achieve human-like performance; sensor-integrated grippers that can safely and effectively handle unknown objects are the end goal.

Yi, B., et al. [20] introduced a new parallel-type robotic gripper with a parallelogrammic platform designed to flexibly fold and conform and to grasp irregular or larger objects, as well as follow precise micro-positioning. The study utilized a design, model, optimize, and experimentally validate approach to creating a configuration-controllable gripper for handling many shapes and performing accurate post-grasp changes. The approach used mathematical modeling for direct and inverse kinematics, force control, and workspace analysis. Optimization was achieved with both single and composite indices like isotropy and grasping force that were completed with a genetic algorithm. Pneumatic actuation with a custom miniaturized proportional valve was applied to the gripper, while utilizing motion tracking and using pressure and motion feedback for indirect force measurements. The results of the study demonstrated the gripper successfully grasped irregular and large objects while achieving high-precision micro-positioning. The experimental validation showed the gripper was able to successfully track motion while using it to demonstrate indirect force control enabled by pneumatic actuation. The study proposed research gaps, while considering the practical errors observed during testing, such as friction generated in the pneumatic actuators and the difficulty of initializing each respective actuator smoothly. The study suggested improving reliability and increasing application of the gripper as necessary improvements the gripper would need to make would be to improve actuator sensitivity as well as improve pneumatic actuator friction.

3. Methodology

This research employs an experimental comparative design to investigate the impacts of internal structural geometries on the functioning of 3D-printed soft grippers constructed from thermoplastic polyurethane (TPU). Three types of internal geometries: circular, linear, and zigzag, were proposed to examine the consequences of structure on performance criteria including grip force, deformation range, adaptability, slip resistance, and durability. The material (TPU) is constant while the geometry is varied, thus performance differences observed are due to internal structure variation and not material variation. The experimental process was separated into three experimental components: design, fabrication, and evaluation.

Thermoplastic polyurethane (TPU) was selected for the fabrication material in this study due to its particular combination of flexibility, durability, and relative ease of processing as a suitable material to use for soft robotics. Unlike rigid polymers, TPU can be formulated to have a very high elongation at break, typically ranging anywhere between 400–600%, and consequently allows for considerable deformation in the gripper claws without rupture. This elasticity of TPU is especially valuable for soft gripper design as it provides the potential for adaptive and safe grasping of fragile or irregularly shaped objects. TPU also offers high fatigue resistance, meaning that it retains its mechanical properties across repeated cycles of loading and unloading. This resistance to fatigue assists in evaluating the long-term durability of the claws under cyclic actuation. TPU has favorable surface properties for gripping as its higher coefficient of friction minimizes slip between the claw surface and smooth or delicate objects, which improves overall grasping stability. On a practical level, TPU is also compatible with the fused deposition modeling (FDM) 3D printing process with an ability to precisely control the internal geometry of the claws and a quick, repeatable prototyping capability. The increased use of TPU in industrial and consumer applications (wearable devices, cushioning systems, and robotic components) supports its relevance and practicality as a research material. TPU is favored as a material of choice compared to other soft gripper materials (silicone elastomers, natural rubber, and hydrogels) that are commonly used in dynamic gripper applications, because TPU offers an outstanding balance of: mechanical strength, flexibility, and can be manufactured. Lastly, silicone is very compliant and biocompatible and offers high elasticity but an undesirable tear resistance and durability to cyclic loads, which lead to mechanical failure during repeated grasps. Natural rubber offers suitable elasticity and bold strength but is susceptible to degradation over time from environmental factors, such as ozone exposure and its limited design freedom of additive manufacturing. Hydrogels are great materials for their highly adaptive and bioinspired gripping because of their extreme softness but have low tensile strength, high water content, and insufficient stability for long-term use which limits their applicability for industrial or high-load applications. TPU provides a balance of the elasticity necessary for an adaptive grip while maintaining high tensile strength, abrasion resistance, and elongation at break providing the material with the strength to sustain repeated deformations while maintaining structural integrity. Considering possible additions, TPU can be fabricated using modern additive manufacturing methods like fused filament fabrication (FFF) and selective laser sintering (SLS), which are more viable and scalable than cast silicone or hydrogel systems due to lower fabrication time and costs. The combined mechanical properties of TPU provide for a more robust maze of elasticity and tensile strength than rubber or hydrogel making it a more reliable and versatile material option for soft robotic grippers operating in both research and industrial design settings.

Apart from the specified material selection, our project is interested in three internal geometries: circular, linear, and zigzag since the inner structure of the soft gripper relates to its mechanical behaviors during actuation. Circular geometry provides isotropic deformation, meaning that bending flexibility occurs uniformly in a variety of bending directions. This will enhance adaptability to non-uniform or rounded object surfaces, despite likely resulting in lower maximum grip force due to the reduced stiffness. Linear geometry, on the other hand, establishes directional compliance in the line's axis that provides greater grip strength and stability in interactions with symmetrical objects. Similarly, adapting to non-uniform shapes is limited with this design. Zigzag geometry establishes an alternating internal stress path that includes flexibility and stiffness elements. It is believed that this hybrid structure will better balance between flexibility and grip force, and while not assumed, provide some torsional stress resistance compared to either strict line or circular structural designs. The gripper is a tendon-driven assembly actuated by a single rotary servo.

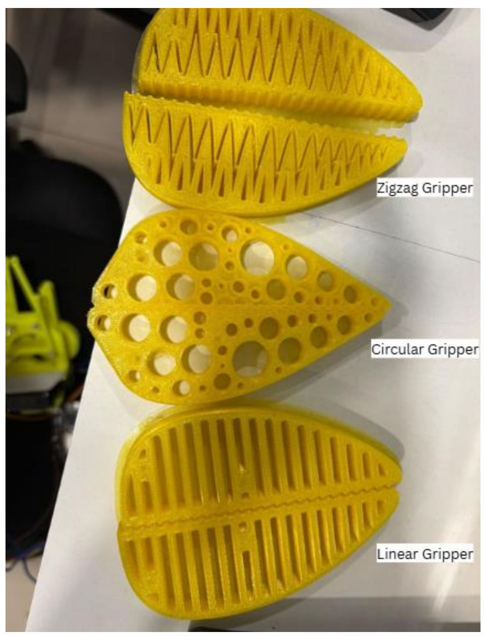

Figure 1. TPU Printed Grippers with Different Internal Geometries

By selecting TPU as the constant material and varying only the internal geometrical structures, this study aims to isolate and compare the effects of geometry on gripper performance. This approach not only ensures that performance differences can be directly attributed to geometry but also provides insight into the trade-offs and synergies between structural design and material properties.

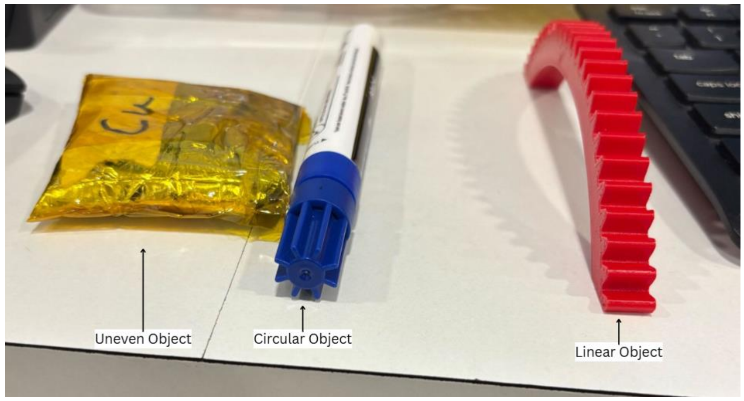

Figure 2. Different Objects used

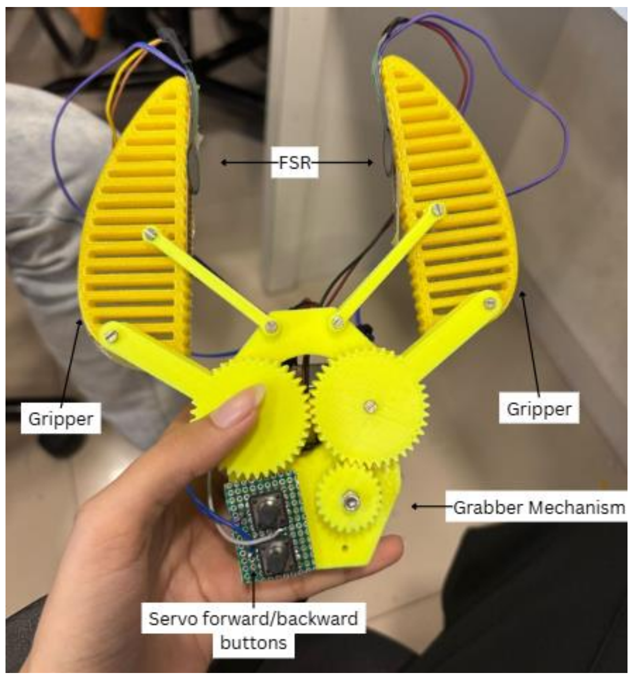

Figure 3. Grabber Mechanism

The gripper mechanism was built with a servo motor connecting to a spur gear train that converts rotary movement into symmetric linear motion of the two gripping arms. The servo motor is controlled with dedicated forward and backward buttons embedded into the gripper case, which enables user control when actuating the gripper in either direction. The dimensions of the jaws are modular, allowing for three different internal shapes linear, circular, and zigzag designed with a made-out-of TPU material, allowing for manipulation and investigation on how surface topology affects distributed gripping forces. Force Sensitive Resistors (FSRs) were incorporated along the inner gripping surfaces to measure real-time contact force at the point of manipulation. In the experiment, the jaws are grasping three representative object types linear, circular, and uneven with passes applied under the same actuation process. For every trial, the servo motor would be commanded to turn at a constant angular displacement rate while the jaws close until the gripper firmly contacts the object, while the FSR continuously writes down normal force values each trial. An ESP microcontroller was used as the central processing unit for this experimental process with actuation and sensing responsibilities. The servo mechanism that actuates the gear-based grabber was wired to the ESP, with a pair of momentary push-buttons controlling forward and backward rotation of the servo shaft.

This controlled actuation facilitates repeatability of the gripper jaw's opening and closing. Strain gauges, termed Force Sensitive Resistors (FSR), are integrated into the inner contact surfaces of the grippers to quantify the gripping force. Each FSR is interfaced to the ESP using a voltage divider circuit; the FSR functions as a variable resistance/load, whereby the resistive variation under load transduces to an analog voltage output. As the gripper jaws apply grip to the object, the mechanical pressure contacts the FSR and compresses the material, consequently resulting in a reduction of resistance and a proportional increase in the output voltage signal. The ESP samples the signals using the onboard ADC, and measures the amount of real-time grip force. Each trial, ten consecutive measurements are recorded, repeated across nine trials that represent three internal geometries for the grippers (linear, circular, and zigzag), and three object categories (linear, circular, and uneven). The protocol of consecutive samples measures covariance between observations and serves to reduce stochastic noise, aiding in statistical averaging or measurement reliability and precision. The servo actuation was operated in a standardized protocol over all trials to control for differences in closure speed in the trial convergence, serving to understand the confounding influence of geometry to grip and force distribution. This integrated circuit and sensing architecture provides a robust means of analyzing the relationship between gripper geometry, object shape, and force exertion, thereby yielding insights into the optimization of soft robotic gripping mechanisms.

4. Results and Analysis

The experimental data was used to examine the performance of three distinctly different grabber geometries, Linear, Circular, and Zigzag, on three different objects, Linear, Circular, and Uneven. The main metrics analyzed were the readings from two force-sensitive resistors, FSR 1 and FSR 2, and Flex sensors, which analyzed the distribution and magnitude of the applied grip force.

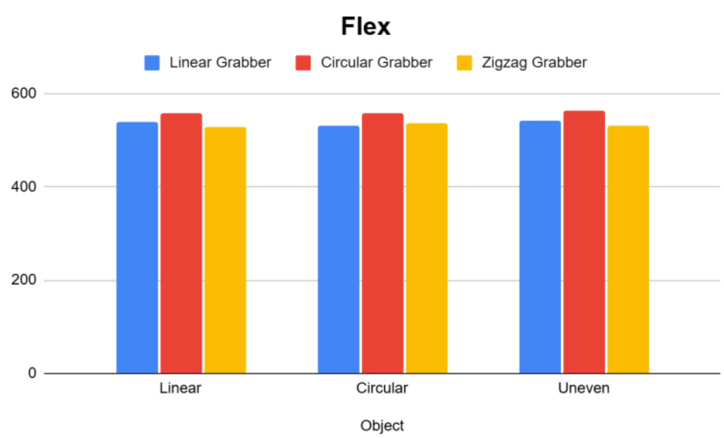

Figure 4. Flexibility of each type of grabber with each type of object

Figure 4 indicates the flexibility measurements for each of the three types of grabbers, Linear, Circular, and Zigzag, for the three types of object shapes, Linear, Circular, and Uneven. In general, each one of the grabbers were fairly consistent in terms of flexibility with values ranging approximately from 500–560. The Circular Grabber had the highest overall flexibility for every object type, slightly surpassing both the Linear Grabber and the Zigzag Grabber in the comparison. The flexibility for the Zigzag Grabber was moderately less than the other two grabbers, although the difference is minimal across design types indicating a similar performance for each design. There was no change in flexibility attributed to object type, demonstrating that grabber design should have a greater impact on flexibility compared to shape of the gripped object.

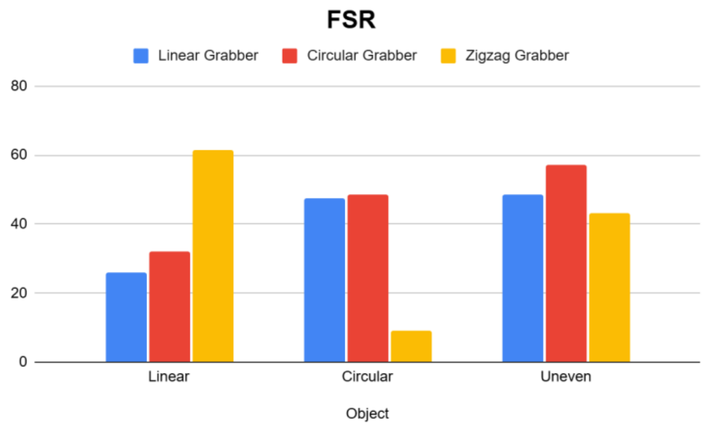

Figure 5. Force for each type of grabber with each type of object

The force exerted by each grabber type, measured by force-sensitive resistors (FSRs), is illustrated in Figure 5 using the same object types. These results show different trends than the flexibility data with grabber performance being more influenced by grabber type as well as object geometry. For Linear objects, the Zigzag Grabber applied the most force (~61) compared to Linear (~26) and Circular (~32) grabbers. This suggests that the Zigzag configuration is most effective at generating grip force on objects with consistent geometry. Referring to Circular objects, the Linear and Circular Grabbers both applied similar force (~48); however, the Zigzag applied very little force (~9). This suggests that Zigzag design is ineffective at gripping objects that are round shaped. The Zigzag design may not be applied to uniform geometry of round objects due to creating less conforming surfaces that contact the object. Lastly, when examining the Uneven objects, the Circular Grabber applied the most force found (~57) while the Linear and Zigzag Grabbers (~48 and ~43 respectively) showed less force applied. This follows the pattern of the Circular Grabber being very adaptable to odd shapes and designs while the Zigzag was somewhat effective.

If long straight shapes are the preferred options for linear products, the Linear grabber is the ideal style of grabber as its design can lay flat on linear surfaces for good contact and a strong grip to act on a straight-edge surface. However, linear grabbers have difficulty adapting to the shape of circular or uneven objects with curves, which results in weak and inconsistent grips. Its application is not adaptable and limited when factors of curves or uneven surfaces are present. On the other hand, the Circular grabber is indicated for circular and uneven objects, displaying when its geometry allows itself to adapt naturally to the curved object or an uneven surface providing grip you can depend on. It is very effective when you need grip adaptability to seek access to circular and uneven or irregular objects. The Circular grabber performs less effectively when working with linear objects, but is still capable of adequately holding linear shapes with moderate stability, again demonstrating some flexibility of application. The Zigzag grabber is very effective for linear objects as it provides grip that is firm and stable both when working on standard linear objects and uneven or irregular objects with your treatment design. The Zigzag grabber does not work well for circular objects as the Zigzag shape will not conform adequately to access the circular dimensions which leads to weak grip performance.

5. Conclusion

This study systematically investigated the influence of internal geometrical structures circular, linear, and zigzag on the performance of soft grippers fabricated from thermoplastic polyurethane (TPU). By keeping the material constant and varying only the internal geometry, the results clearly demonstrated that geometry is a critical factor shaping the balance between grip force, deformation range, adaptability, slip resistance, and durability.

The results demonstrate that gripper geometry is a critical determinant of performance. The Linear gripper excels in handling linear objects, delivering firm and stable grip but showing limited adaptability to non-linear or irregular shapes. The Circular gripper, in contrast, exhibits superior adaptability, conforming effectively to circular and uneven objects, making it ideal for tasks requiring versatile and secure grasping of irregular shapes. The Zigzag gripper offers a balanced compromise between strength and flexibility, performing reliably with linear and uneven objects but underperforming with circular objects.

This research systematically examined the effects of internal geometrical structure - circular, linear and zigzag - on the performance of soft grippers fabricated from thermoplastic polyurethane (TPU). The outcomes clearly showed that geometry plays a significant role in balancing grip force, deformation range, adaptability, slip resistance, and durability, while keeping the material the same and just changing internal geometry.

The outcomes indicate that gripper geometry is an important determining factor of performance. The Linear gripper is most effective at processing linear objects, exhibiting a strong, stable grip with limited adaptability to non-linear or irregular shapes. The Circular gripper, on the other hand, considerably extends adaptability even to circular or uneven objects making it the best design for work requiring a versatile, secure grasp of irregular shapes. The Zigzag gripper provides a middle ground between strength and flexibility, but is less effective with circular objects when compared to the Circular gripper, but is effective for linear and uneven objects.

In conclusion, this research emphasises on the interdependence between geometry and material for performance. While TPU proves to be a durable material, internal geometry does have an impact on task specified performance. Future work should focus on the comparative framework by using multi-material printing, and dynamic control mechanisms to ensure adaptability, strength, and reliability.

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