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ADDITIVE MANUFACTURING OF PNEUMATICALLY ACTUATED SOFT ROBOTIC GRIPPERS: ENABLING COMPLEX GEOMETRIES AND CONFIGURATIONS

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Abstract: *This paper presents the design, fabrication, and testing of a pneumatically actuated soft gripper manufactured via multimaterial 3D printing (FDM), combining flexible TPU 40D segments with PLA structural elements for stiffening and modular assembly. The biomimetic geometry – drawing inspiration from the segmented locomotion of caterpillars – integrates three "fingers" with internal pneumatic channels and partially fused chambers, optimized to deliver controlled elastic deformation while meeting AM design constraints (minimum wall thicknesses, overhang angles ≥ 45°, and avoidance of long unsupported bridges). The fabrication strategy included mid-print PLA inserts for anchoring, sliding-fit gaps of 0.05–0.15 mm, and a teardrop-shaped internal channel to minimize unsupported spans and improve process repeatability. Preliminary tests showed (i) a smooth and predictable bending response of a single finger at ≈ 1–3 bar, validating the material choice and chamber configuration, and (ii) reduced performance of the three-finger assembly due to air leaks at the interfaces, underscoring the importance of sealing and robust pneumatic distribution. Improvement directions include the use of O-rings/gaskets, fine pressure regulation, and integration of sensors for closed-loop control. The results indicate that 3D-printed soft grippers can combine adaptability, customization, and cost efficiency for delicate manipulation, paving the way for industrial and medical applications where safe interaction with fragile objects is critical.*

Key words: *additive manufacturing, robotics, pneumatics, thermoplastic polyurethane, soft grippers.*

1. INTRODUCTION

Soft robotic grippers must safely manipulate fragile, irregular objects while remaining compact, reliable, and economical. Conventional molding-based fabrication struggles with internal pneumatic channels, undercuts, and consistent sealing; early 3D-printed designs often trade flexibility for rigidity or require assembly-intensive workflows that are hard to reproduce at scale. These limitations hinder predictable deformation, airtightness, and repeatable fabrication in practical settings.

Prior work mitigates bubbles and shrinkage in cast elastomers (e.g., vacuum degassing, centrifugal casting, packing pressure) and explores multi-part molding and low-cost casting routes, including water-soluble cores, to realize complex cavities. In parallel, additive manufacturing (AM) for soft robotics has advanced toward total AM and embedded multi-material printing, improving geometric freedom and enabling programmable motions; however, leak-free interfaces and robust, reproducible builds remain open challenges.

We design, fabricate, and test a pneumatically actuated soft gripper produced by multimaterial fused-deposition modeling (FDM). The device combines TPU 40D fingers for compliance with PLA structural elements for anchoring and modular assembly. We implement a mid-print PLA insertion workflow, define TPU-specific design/print rules (e.g., wall thicknesses, overhang limits, sliding-fit tolerances), and evaluate single-finger and three-finger assemblies under pneumatic actuation.

Our approach introduces a biomimetic three-finger architecture with partially fused chambers and a teardrop-section internal channel explicitly tailored to FDM constraints, alongside mechanically interlocked PLA inserts added mid-print – eliminating adhesives while improving structural anchoring and manufacturability. We codify practical, reproducible guidelines that couple geometry with print parameters for TPU 40D to achieve predictable bending at ≈ 1–3 bar in single-finger tests.

We provide an end-to-end, replicable workflow, from CAD through print parameters and assembly to testing, plus a comparative assessment of single-finger versus assembled-gripper behavior that diagnoses performance losses to interface leaks. We translate these findings into concrete improvements (O-rings/gaskets, fine pressure regulation, embedded sensing) to guide further research toward closed-loop, leak-resilient soft grippers.

The remainder of the paper is organized as follows: Section 2 reviews the state of the art. Section 3

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introduces details materials, parameters, and the fabrication workflow. Section 4 presents the proposed design. Section 5 reports testing and results. Section 6 outlines further research and Section 7 resumes conclusions.

2. STATE OF THE ART

2.1. Conventional manufacturing techniques

Most soft robotic components are fabricated from catalyzed polymers, such as silicone rubbers, which are prepared by mixing two separate components before molding. However, the mixing process often introduces air bubbles into the material, which cand compromise structural integrity. Mazzeo and Hardt demonstrated that some useful methods to address this are vacuum degassing or even spinning the mold in order to use centrifugal forces so as to more effectively remove trapped air [1].

Thermoplastic materials like paraffin wax can suffer from shrinkage during cooling, leading to deformation or dimensional errors. A solution to compensate for this setback has been studied by Polygerinos et al., concluding that materials should be molded under packing pressure during cooling, which provides additional material to offset shrinkage [2].

A significant limitation of conventional molding is the creation of internal volumes and undercuts. While molds efficiently form external shapes, internal cavities are challenging to extract without damaging the part. Tolley et al. have proposed some approaches to this disadvantage such as molding multiple subparts followed by gluing or dipping in uncured material. However, these approaches may create structurally weaker seams [3].

Bell et al. introduced a low-cost injection molding process specifically for soft robots, enabling rapid prototyping of silicone parts. This approach lowers equipment cost and silicone volume requirements by using 3D-printed molds and static mixers, significantly reducing bubble defects and improving consistency in soft actuator fabrication [4].

Silva et al. demonstrated an integrated single-step casting method for soft pneumatic actuators. They have 3D-printed molds and water-soluble cores, which were dissolved after casting, allowing complex internal cavities without assembly. This technique yields actuators with non-uniform cross-sections in one molding step, accelerating development and avoiding weak seams from multi-part bonding [5].

Ishikawa et al. developed an in-vacuum silicone molding process to eliminate air entrapment in soft robot parts. By controlling the silicone pour point inside a vacuum chamber with a parallel-link manipulator, they successfully cast silicone structures without any voids or bubbles, even for intricate shapes [6]. This method improved molding reliability and allowed simultaneous casting of multiple parts for efficient fabrication.

2.2. Additive manufacturing for Soft Robotics

Additive manufacturing fabricates objects by locally depositing material to form directly the desired shape, as stated by Kruth [7]. AM techniques have evolved from producing primarily rigid thermoset polymers to supporting a wide variety of flexible and multi-material prints. Common AM methods include stereolithography (SLA), selective laser sintering (SLS), and fused deposition modeling (FDM). SLA polymerizes small volumes of liquid pre-polymer using a focused laser, while SLS fuses powdered material layer by layer.

AM provides greater freedom to design complex geometries, including entangled and convoluted shapes that are difficult or even impossible to achieve with machining or molding. Overhangs often require support structures, which can be removed mechanically or chemically. Design constraints such as draft angles and overhang lengths must be respected to avoid sagging, holes or mechanical weaknesses, guidelines studied by Anver et al. [8].

Stano & Percoco provided a comprehensive review of additive manufacturing (AM) in soft robotics, outlining how 3D printing evolved to fabricate soft devices. They classify three AM approaches – rapid mold fabrication, hybrid fabrication, and total AM – and note that fully printed soft robots (total AM) offer the greatest design freedom. With advances in printable materials (elastomers, conductive inks, etc.), AM is poised to supersede traditional molding for complex soft robots [9].

Wang et al. presented a multi-material embedded 3D printing method (ME3P) for soft actuators. Instead of labor-intensive multi-step casting, this technique directly prints elastomer and fiber composite inks together to create fiber-reinforced soft actuators in one go. Their approach improved fabrication flexibility and produced pneumatic actuators with programmable motions (elongation, bending, twisting, etc.), showcasing the versatility of embedded printing for soft robot manufacturing [10].

Kanhere et al. developed an in situ free-form 3D printing strategy to repair and upgrade existing soft robots. The method uses a support gel that conforms to a robot's surface, allowing new soft material features to be printed directly onto it in multiple materials. After curing, the gel is washed away, leaving the new components seamlessly integrated. This enables precise additions (e.g. sensors, new actuators) to aging soft robots, highlighting a novel way to extend robot lifespan and functionality via additive manufacturing [11].

3. MANUFACTURING METHODOLOGY

3.1. Materials and Equipment

The experiments were conducted on an FDM printer equipped with a Ø0.4 mm nozzle and a heated build plate, with the slicing workflow configured to support "pause at height"/filament change for mid-print insertions. The materials used were TPU 40D (Fiberflex 40D) for compliant elements and PLA (Polymaker PLA Pro) for structural features, prepared with Cura or PrusaSlicer using custom FDM profiles tailored to each polymer. Routine consumables included bed-cleaning supplies (tape and isopropyl alcohol) and a light, optional adhesive for external interfaces, while dimensional checks were performed with a caliper; pneumatic characterization employed a compressor with a pressure regulator.

Table 1

FDM Parameters Used

Parameter	TPU 40D – Fiberflex 40D	PLA – Polymaker PLA Pro
Nozzle size	0.4 mm	0.4 mm
Layer height	0.20 mm	0.20 mm
Nozzle temperature	230 °C	210 °C
Bed temperature	50 °C	60 °C
Printing speed	25–80 mm/s (recommended: 30–45 mm/s for perimeters on airtight parts)	40–200 mm/s (recommended: 40–80 mm/s for accuracy)
Infill	15% Gyroid	15% Gyroid
Bottom/Top layers	4 bottom, 5 top	4 bottom, 5 top
Perimeters	2	2

3.2. Printing Parameters (FDM)

Table 1 summarizes the settings used for the compliant segments (TPU 40D) and the structural/insert elements (PLA).

3.3. Workflow for Mid-Print PLA Insertion (mechanical anchoring)

To illustrate the application of parametric modelling automation in hybrid material design, a gear incorporating PLA inserts within a TPU matrix was developed. The fabrication procedure was structured as follows:

1. *CAD modelling.* A parametric CAD model was created, defining seats for the PLA inserts within the TPU body. The dimensions of these seats were driven by parameters controlling insert geometry and gear dimensions, ensuring precise positioning (Fig. 1).
2. *Slicing and pause-at-height setup*. During slicing, a pause command was introduced immediately after the completion of the layers forming the insert seats. The pause included head parking and controlled resumption, enabling accurate placement of the inserts.
3. *Start of TPU print*. The process was initiated with TPU filament, which was printed up to the designated pause height, thus forming cavities ready to accommodate the PLA inserts.
4. *Insertion of PLA components*. At the programmed pause, the separately printed PLA inserts were placed into their respective seats. Each insert was pressed firmly to ensure full seating and alignment within the TPU matrix (Fig. 1).
5. *Resumption of TPU print*. Printing was resumed, with subsequent TPU layers enclosing the PLA inserts. This created a mechanical interlock, leveraging the strong adhesion of TPU on PLA.
6. *Hot process check*. The first resumed layers were observed carefully to identify any signs of insert misalignment or lifting. In the event of displacement, the print would be cancelled to avoid material waste.
7. *Cooling and inspection*. After completion of the printing process, the component was allowed to cool to ambient temperature. The hybrid interface was then inspected for TPU–PLA bonding quality, surface flatness, and dimensional accuracy.

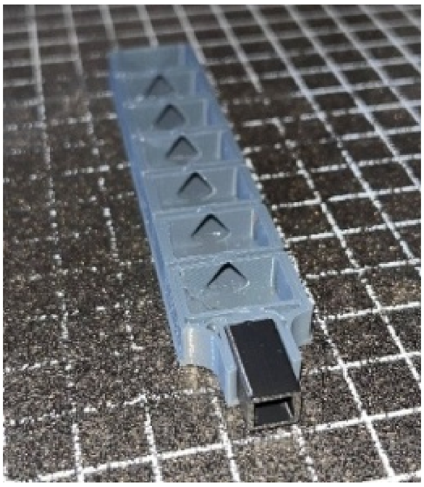

Fig. 1. Mid-print PLA insertion workflow during TPU printing.

4. PROPOSED SOLUTION – CASE STUDY

The proposed solution focuses on the design and fabrication of a nature-inspired soft robotic gripper, drawing inspiration from the locomotion and flexibility of caterpillars. The gripper is intended to interact safely with a variety of objects, utilizing compliance and adaptability to accommodate diverse shapes and fragilities. To achieve these objectives, the gripper is constructed using additive manufacturing, namely fused deposition modeling (FDM), employing a combination of thermoplastic polyurethane (TPU 40D) and polylactic acid (PLA) to realize a multimaterial structure.

Thermoplastic polyurethane 40D is a flexible, elastomeric polymer characterized by a Shore hardness of 40 on the D scale, placing it in a moderate range of softness and rigidity.

This material combines elasticity, durability and resilience, allowing it to undergo repeated stretching, bending and compression while returning to its original shape. TPU 40D's molecular structure consists of alternating soft and hard segments, where the soft segments provide flexibility, and the hard segments act as physical crosslinks that maintain structural integrity. When used in soft robotics, these properties enable the material to deform elastically under pneumatic actuation, conform to irregular surfaces, and withstand cyclic loading, making it ideal for grippers and other compliant actuators.

The gripper (Fig. 2) consists of three individual fingers (Fig. 3), each designed to fold inward then pressurized air is introduced into the internal channels. This folding mechanism enables the gripper to conform around objects of varying geometries, providing a gentle yet secure grasp. Each finger incorporates a continuous internal channel that connects multiple compartments or "rooms" (Fig. 3). These compartments are designed to only be partially fused, to allow for the elastic deformation of the finger while still maintaining structural integrity (Figs. 2 and 3). Each finger has a total height of 18.5 mm, length of 102 mm, width of 21.2 mm. The chambers are fused over a span of 14 mm and the internal channel measures 6.6 by 6.4 mm. All these dimensions enable the fingers to achieve elastic deformation, effective load distribution and reliable

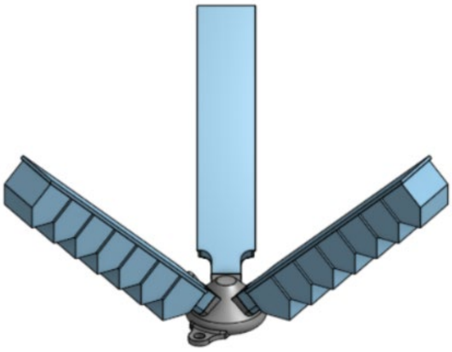

Fig. 2. CAD model of Gripper.

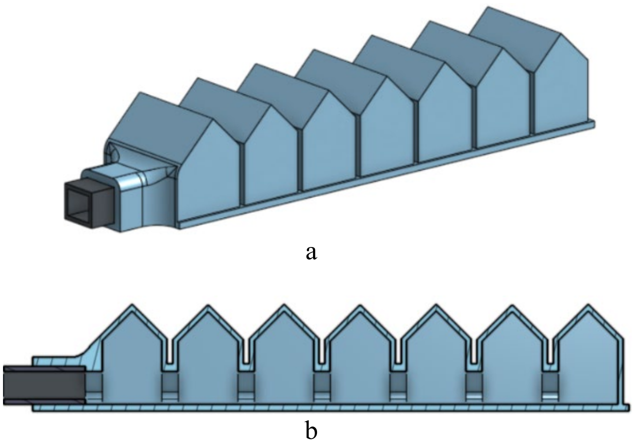

Fig. 3. CAD model of finger: *a* – isometric view; *b* – Section through longitudinal plane of CAD model of finger.

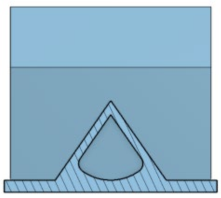

Fig. 4. Section through front plane of CAD model of finger.

pneumatic actuation, resulting in a gripper that is both delicate and resistant.

The internal pneumatic channels use a teardrop cross-section, as you can see in Fig. 4, oriented with the tip upward. This choice removes the unsupported horizontal "ceiling" inherent to circular or rectangular sections and replaces the critical flat span with a continuously sloped arch. For FDM, this yields: (i) preservation of the channel opening without collapse of the top layer, (ii) reduced porosity at edges, and (iii) improved repeatability at operating pressures (≈ 1–3 bar), since the extruded beads follow a steadily inclined path.

Fabrication of the fingers is carried out by multimaterial 3D printing, combining the flexibility of TPU 40D for the soft, deformable regions with the rigidity of PLA for structural supports and assembly features. The PLA inserts are printed first, after which the printing of the soft TPU segments is started. Unlike printing with PLA, the soft segments must be printed individually rather than in batches, in order to prevent the previously deposited layers from drying before the new ones are applied, as TPU poses greater challenges in this regard. The print of the soft segments is paused at a mid-layer stage to allow for the insertion of PLA components, which serve as anchoring structures in the final assembly. Once the PLA inserts are positioned, printing is resumed. The inherent compatibility between TPU and PLA ensures that the materials fuse together, creating a strong bond without the need for additional adhesives.

Following the fabrication of the individual fingers, the assembly is completed by integrating the three fingers into a PLA-printed base. This base includes precision holes for finger attachments as well as an opening to accommodate the pneumatic air supply (Fig. 5).

An important aspect when designing these components was following the design constraints imposed by additive manufacturing, in order to guarantee both manufacturability and long-term structural integrity. Among the most critical factors is the maintenance of minimum wall thickness, which is necessary to prevent collapsing. Similarly, overhangs and unsupported spans must be designed within permitted angular limits to minimize the risk of sagging, warping or incomplete layer adhesion during the printing process. These constraints become even more rigorous when working with TPU 40D filament, a material known for its increased printing complexity compared to more rigid thermoplastics such as PLA.

To address these challenges, the geometry of the gripper's fingers was carefully optimized to comply with the previously stated principles. Specifically, no walls were inclined at angles less than 45 °, thus reducing the possibility of deformation in unsupported regions, while fully horizontal bridges were deliberately avoided except in one controlled location above the PLA insertion. The internal pneumatic channel was designed with a teardrop-shaped cross-section, a design strategy that minimizes sharp edges and long unsupported spans.

Furthermore, the wall thickness distribution was refined through iterative prototyping and experimental testing. The final configuration consists of 0.9 mm upper walls to provide flexibility for actuation, and 2.2 mm lateral walls to supply additional reinforcement against stress. The rationale is twofold: at the extrados, thinning to 0.9 mm reduces bending stiffness and enables large curvature at moderate pressures; on the sidewalls, 2.2 mm stabilizes the chamber geometry and distributes stresses at the rib roots, lowering the risk of "ballooning" or micro-cracks along the bead roots. This configuration

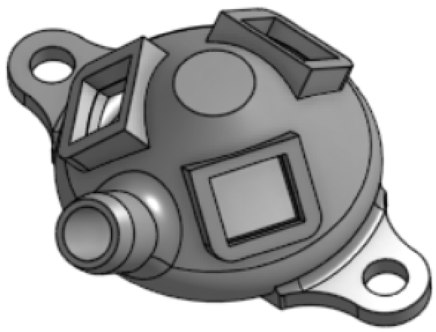

Fig. 5. Base of gripper.

was found to offer the optimal balance between elasticity and durability, enabling fingers to deform predictably under pneumatic pressure while resisting unwanted deformation.

By respecting the previously outlined design principles, the 3D printing of the TPU 40D soft finger components (Fig. 6) and the PLA gripper base (Fig. 7) was achieved with high accuracy to the CAD model. The sliding-fit gap of approximately 0.05–0.15 mm used in designing the assembly between the fingers and the base ensured both ease of insertion and sufficient stability, resulting in the finalized gripper configuration illustrated in Fig. 8.

Overall, this solution combines biomimetic design principles, multimaterial additive manufacturing and careful material selection to create a soft robotic gripper that is compliant and easy to fabricate. The use of TPU 40D ensures sufficient elasticity for delicate interactions, while the PLA insertions provide structural support and facilitate and assembling.

The design allows for the rapid prototyping of complex geometries, demonstrating the potential of 3D printing for creating versatile and functional soft robotic systems.

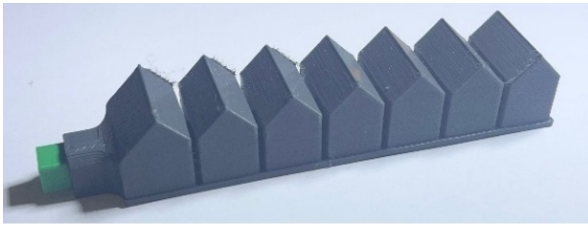

Fig. 6. 3D printed finger.

Fig. 7. 3D printed gripper base.

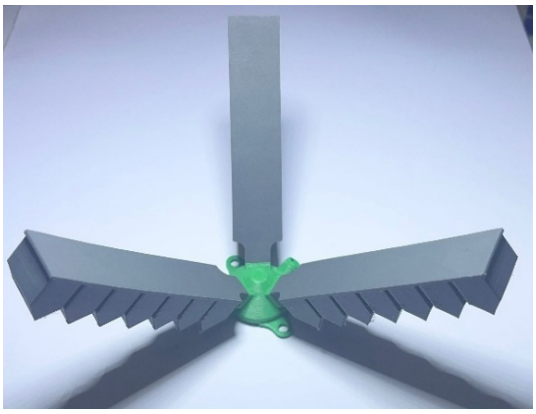

Fig. 8. Final gripper assembly.

5. TESTING AND RESULTS

The performance of the proposed soft robotic gripper was evaluated through a serious of pneumatic actuation tests using a controlled air pump as the pressure source.

The first stage of testing involved the individual actuation of a single finger. In this configuration, the air pump was directly connected to the finger's internal channel. The results demonstrated that the finger bent smoothly and predictably when subjected to an input pressure of approximately 2.6 bars, as pictured in Fig. 9.

Figures 10 and 11 present the FEA of one finger, confirming the effectiveness of the design and the suitability of TPU 40D for achieving controlled elastic deformation.

The second stage consisted of testing the complete gripper assembly, composed of three fingers mounted onto the PLA base. In this setup, the pneumatic system was required to distribute pressurized air simultaneously across multiple channels. It was observed that the increased complexity of the pneumatic circuit introduced air leakage at several junctions, namely at the coupling interfaces between the fingers and the base, respectively

Fig. 9. Testing of individual finger. Configuration of testing includes a controlled air pump connected directly to the finger's internal channel.

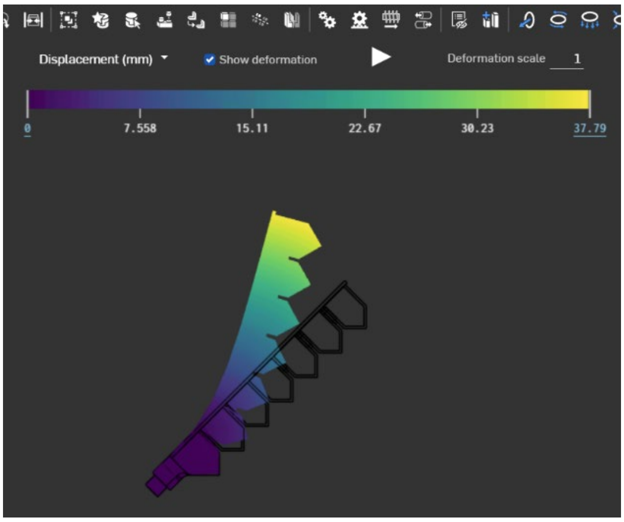

Fig. 10. Total displacement of the finger under internal pressurization of 1 bar; the color scale indicates the displacement amplitude (mm).

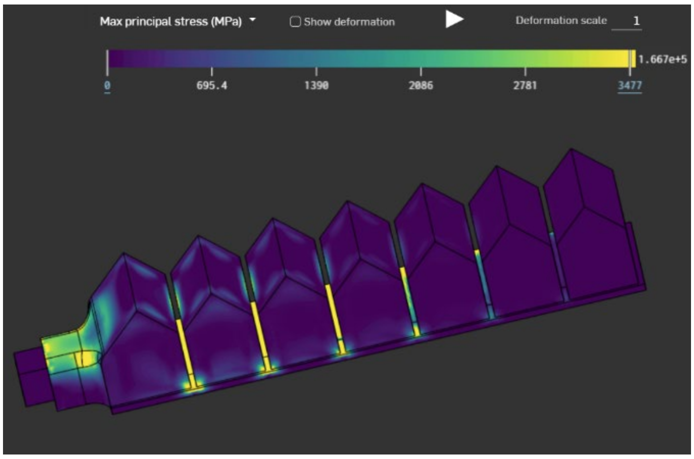

Fig. 11. Maximum principal stress; hot regions mark concentrations at the inlet, rib roots, and between chambers; deformation is shown at the indicated scale.

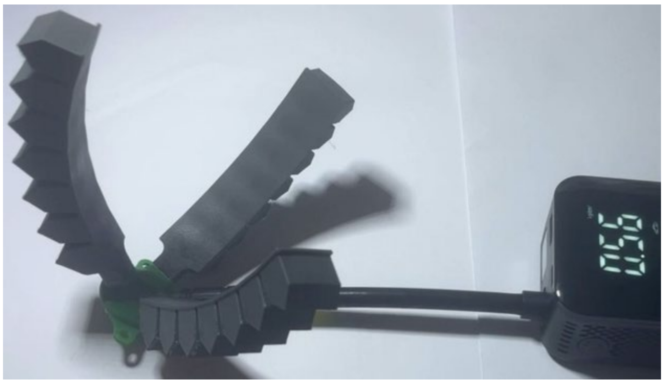

Fig. 12. Testing of gripper assembly. Configuration of testing includes a controlled air pump connected to the gripper base through the pneumatic opening.

at the pneumatic inlet linking the air supply to the base, as underlined in Fig. 12, which resulted in a reduction of effective pressure, reaching a maximum of 0.56 bars.

Consequently, the bending performance of the fingers was less pronounced compared to the first test. Although the gripper still demonstrated considerable deformation under actuation, the reduced efficiency raised concerns about its ability to perform reliable and stable object manipulation tasks in the current stage of development.

6. FUTURE IMPROVEMENTS

The results of the initial testing suggest several opportunities for improvement in order to enhance the gripper's functional performance. The most pressing concern involves air leakage within the pneumatic system, which could be mitigated by integrating more effective sealing methods, such as O-rings, gaskets, or the use of airtight adhesives at critical interfaces.

Additionally, the incorporation of a pressure regulation mechanism, which would allow fine-tuned control of the supplied air would improve both the consistency and responsiveness of the actuator.

To furthermore complement the pneumatic system, feedback mechanisms such as embedded pressure sensors within the air circuit and bending or strain sensor withing the TPU fingers to enable closed-loop control and significantly improve the gripper's reliability during object manipulation.

Finally, in order to support replicability and further research, the bill of materials can be found below:

- TPU 40D filament for the soft finger structures;
- PLA filament for the gripper base and structural parts;
- O-rings or gaskets for sealing;
- Airtight adhesive (e.g., silicone-based);
- Pressure regulator (0–3 bar range);
- Miniature air pump and tubing;
- Pressure sensor (0–5 bar range);
- Bend/strain sensor (flexible type).

Together, these improvements provide a pathway toward refining the gripper's performance, ensuring that future iterations achieve greater airtightness, more consistent actuation and better adaptability for object manipulation.

7. CONCLUSIONS

This paper demonstrates a practical, fully additively manufactured soft gripper and distills what works and what still needs work for reproducible, airtight TPU-based pneumatic actuators.

Soft grippers must combine gentle, adaptive grasping with repeatable, low-leak fabrication; conventional molding and nave prints struggle with internal channels, sealing, and scalability.

We built a three-finger, biomimetic gripper printed by multimaterial FDM: TPU 40D fingers with internal chambers and a teardrop pneumatic channel, plus mid-print PLA inserts and a PLA base for anchoring and modular assembly. The combination of (i) teardrop channels tuned to FDM limits and (ii) mechanically interlocked, mid-print PLA anchors yield a clean, adhesive-free bond and manufacturable chambers while respecting 45 °/wall-thickness constraints codified as practical design rules.

Single fingers show smooth, predictable bending under pneumatic actuation, validating the geometry/material choice; the assembled gripper's performance is currently limited by air leaks at finger–base and inlet interfaces, which capped the effective manifold pressure to ≈ 0.56 bar.

Performance loss in the assembly is dominated by sealing and distribution, not by finger compliance pointing to interfaces and pneumatic routing as the critical path.

Our contribution is an end-to-end, reproducible workflow (CAD → parameters → mid-print insertion → assembly → tests) plus a clear failure analysis with actionable fixes (O-rings/gaskets, tighter pressure regulation, embedded pressure/bend sensing for closed-loop control).

With improved sealing and regulation, the presented architecture can retain the single-finger actuation quality at system level, enabling gentle, precise manipulation in cost-sensitive settings, advanced soft grippers capable of gentle yet precise manipulation tasks in a variety of applications.

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