Viscous Thread Printing (VTP) for Rapid Production of Custom Soft Robotic Bodies

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***Abstract*—Soft robotic systems are growing in industrial use due to their potential to improve both automation and accessibility technologies. In automated systems, conventionally rigid robots often struggle with handling delicate or irregularly shaped objects, limiting their effectiveness in tasks that require precision and adaptability. Soft robotic bodies constructed from flexible materials, such as foams or thermoplastic polyurethane (TPU), offer a solution that is able to conform to various shapes and apply gentle forces. We demonstrate how to fabricate soft robotic bodies from TPU using Viscous Thread Printing (VTP). Demonstrations of variable stiffness fingers are presented with force to displacement plots and applications are proposed. VTP is shown to rapidly produce adaptive and task-specific soft robotic fingers for compliant applications and open up new opportunities in accessible, collaborative soft robotics.**

***Index Terms*—3D printing, soft robotics, TPU, compliant, VTP**

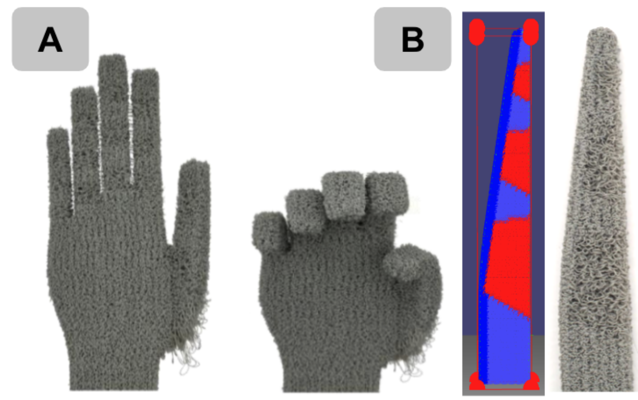

Fig. 1. (A) Viscous thread printing is a method to generate soft robotic structures ready for actuation and instrumentation. (B) Variable density structures are programmed in software for a configured deformation shape.

I. Introduction

Soft robotic systems are growing in industrial use due to their potential to improve both automation and accessibility technologies. In automated systems, conventionally rigid robots often struggle with handling delicate or irregularly shaped objects, limiting their effectiveness in tasks that require adaptability. Soft robotic bodies constructed from flexible materials, such as thermoplastic polyurethane (TPU), offer a solution that is able to conform to various shapes. This makes them ideal for applications ranging from fragile manufacturing to healthcare, where robots need to interact safely with a wide range of objects and humans. Currently, variable stiffness foams are a popular material for building soft robotic systems.

We introduce Viscous Thread Printing (VTP) as a method for creating soft robotic bodies, programmed at fabrication, that achieve a specific deformation under loading. This technology has been demonstrated for a range of materials and print parameters [1]. The technique involves extruding viscous materials as continuous threads, which are deposited into coiling patterns to build up flexible structures layer by layer. Control over nozzle to print geometry allows for the customization of soft robotic bodies with highly variable stiffness and flexibility across contiguous regions. The control of material properties and geometry ensures that the printed bodies can achieve a designed stiffness for a set deformation range according to a known stress.

We produced a set of soft robotic test fingers with equivalent external dimensions while the geometry of internal regions with a lower density was varied. This was done to explore the design space of VTP as a method to produce foams that can serve as soft robotic bodies. To evaluate the displacement of these finger structures, nylon cables were threaded along the joints of test bodies and connected to the finger tip by a servo motor. Each test finger was modeled in software using the COMSOL Multiphysics Solid Mechanics module. Applied pull force to angular deformation in testing and our finite-element model was compared to validate the methodology. This parametric study of finger bodies shows that VTP can be generalized to produce selectively compliant foam structures for soft-robotic systems that can be printed on a low-cost, user-friendly FFF system. The variable density regions of the VTP fingers were shown to behave as homogeneous bodies with different bulk stiffness. This shows that VTP soft robotic bodies can be engineered with reinforced areas for axial strength or torsional stiffness while more pliable sections are used in compliant gripping. Therefore, this VTP method enables the rapid fabrication of adaptive and task-specific soft robotic bodies. Figure 1 shows an example VTP hand and finger designed for a specific deformation under load.

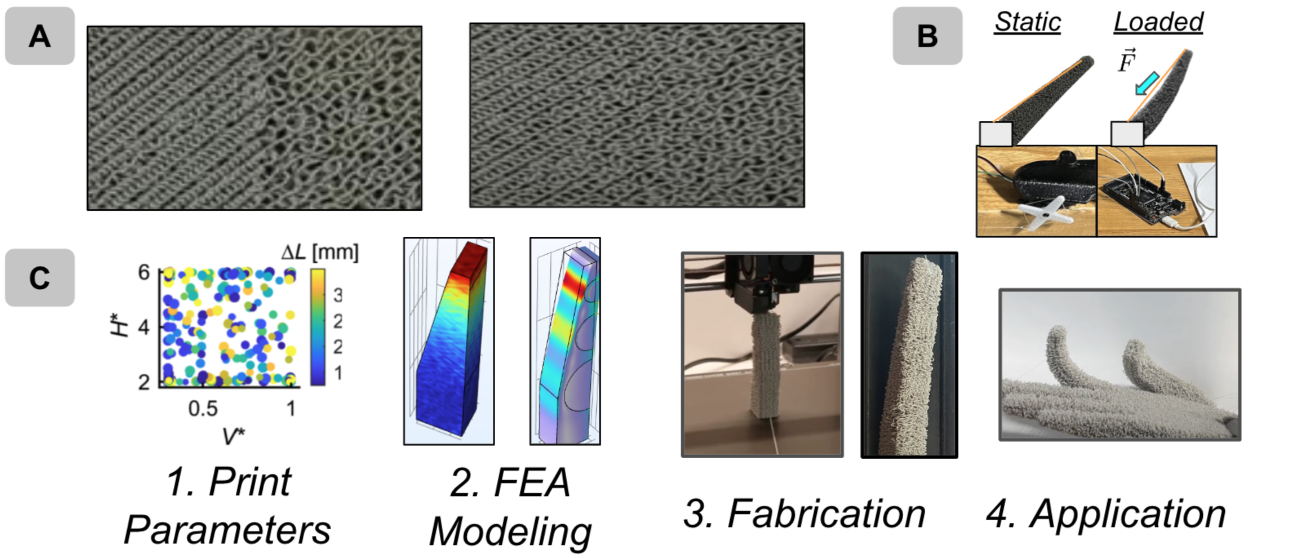

Fig. 2. (A) Viscous thread printing is a method to generate variable density structures with 3D printers. Two different variable density patterns are shown. (B) Variable density structures are driven with servo motors to pull strings threaded through the VTP coils. (C) VTP parameters are chosen to achieve a desired deformation and this can modeled in FEA with homogeneous regions to fabricate for an application.

II. Background

Compliant mechanisms and foam structures have been used extensively in prior work to generate soft bodies for robotics grasping [2]. VTP and similar additive processes have been used for producing variable density structures in soft robotics [3] [4]. In these prior work, authors utilized foams with varying levels of elasticity and mechanical resilience. These foams were shown to exhibit self-stabilizing capabilities and variable stiffness for fragile handling of common goods. In recent years, work in this field has largely focused on manual design iteration and has not leveraged simulation techniques to optimize finger joint design. Computational tools and finite-element methods enables us to optimize for a desired deformation when a soft robotic structure is loaded by a control system. Additionally, past fabrication methods have focused on casting and foam molding instead of digital fabrication techniques.

Applications for prior foam based, soft robotic bodies including flexible electronics and biomedical devices [5]. Tunable and configurational stiffness has shown to be crucial to succeed in these applications [6] [7]. These studies show the versatility of the process and material selection, which can be tuned for specific functional requirements, demonstrating advancement in fabrication for multi-functional and durable soft robotic structures. A limitation noted in prior work on 3D-printed multi-functional foams is in achieving a high range of material properties over the foam structure to avoid crushing the softest handled objects while firmly holding stiff objects [8]. The design space for VTP covers a wide range of densities for conventional FFF materials. By employing VTP as a method for producing soft robotic bodies, we aim to increase the design space for engineers working on soft robotic systems. It is important to also note that additive fabrication processes may not be as easily scaled for industrial applications due to the complexity of controlling the foam architecture and the high costs associated with the specific materials and printing techniques used. This limitation is being handled by parallelizing the print process with multiple nozzles [9].

Soft robotic bodies have been utilized in sign language robots by mimicking the dexterity and nuanced movements of human hands. Compliant bodies allow for adaptive motion, which is crucial for accurately forming complex hand shapes and gestures required for sign language communication. The customization and rapid prototyping capabilities of 3D printing enable the design of intricate, human-like fingers and joints, that can express a wide range of gestures. This innovation could improve communication gaps for the deaf and hard-of-hearing community by enabling more natural and expressive sign language robots. Previous work has shown robots that can perform fingerspelling, translating individual letters through specific finger gestures [10].

Collectively, these prior works illustrate advancements and ongoing research in developing soft robotic systems for soft, compliant grasping as well as improving accessibility.

III. Methods

Viscous thread printing, which involves depositing viscous material as thin threads to induce variable coiling behaviors [1, 11, 12], can be effectively used to fabricate locally programmed variable stiffness foams which demonstrate selective deformation properties useful in applications such as soft robotic fingers. This process begins with selecting and preparing materials like silicone or thermoplastic polyurethane that are viscous enough to maintain their shape upon deposition. In order to reliably produce the desired geometry and stiffness zones of the part, a model mapping input parameters to ho-

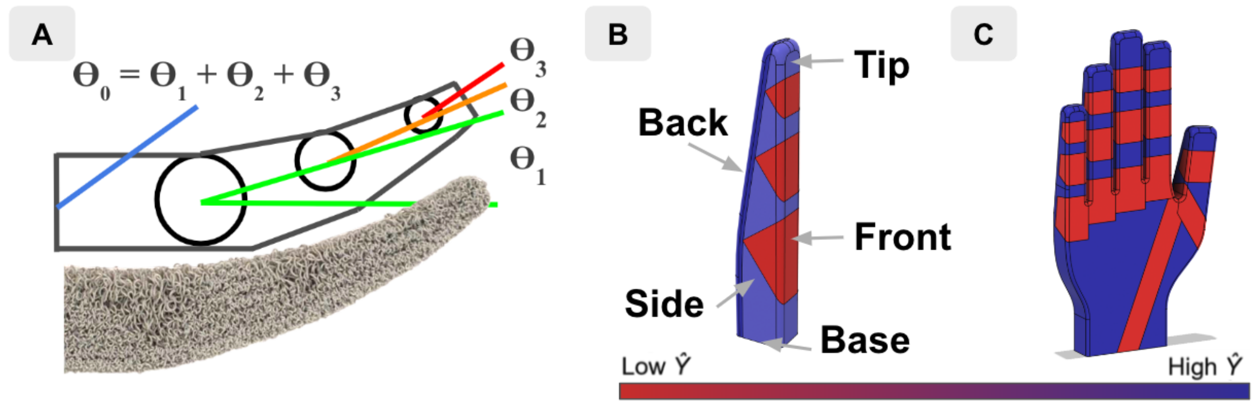

Fig. 3. (A) The revolute joints present in the finger joints for the tested VTP structures. (B) Anatomical terms for the VTP soft fingers. (C) This work is aimed at understanding the force to displacement for a full hand with many degrees of freedom.

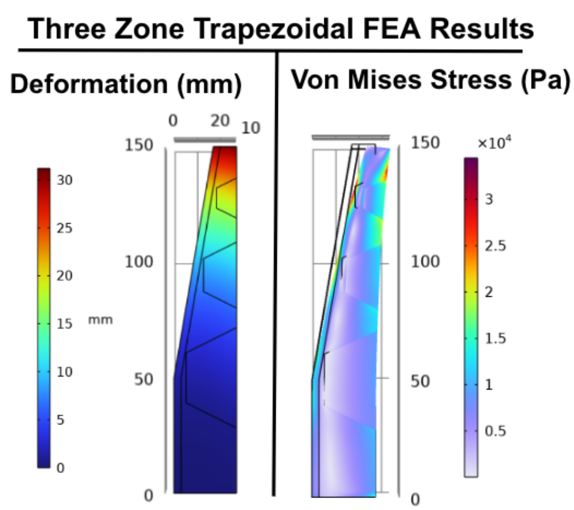

Fig. 4. FEA simulations provided and an estimate of stress and deformation for fixed forces applied to homogeneous soft bodies.

mogeneous output properties was employed [1]. A computer-aided design (CAD) model of the finger, including all desired stiffness zones such as joints and reinforcement areas, was created. This CAD model was then imported into a bespoke slicing software capable of assigning the proper mechanical properties to a rectilinear toolpath according to their respective zones as defined by the model parameters. The material is then extruded layer-by-layer according to the prescribed toolpath, forming the complex geometry of the finger and selective deformation zones. After layer-by-layer printing, the soft robotic finger was then integrated with actuation mechanisms. This was accomplished by threading fishing line up through the already porous surface of the finger and anchoring the line at the fingertip, enabling the cable actuation of fingers and joints. This integration allows for precise control over the finger's movements, which is essential for tasks requiring dexterity and flexibility. The final steps involve testing and calibrating the robotic finger to ensure it functions as intended, including adjustments to optimize performance. Figure 2 shows the fundamental concepts behind this work and a layout of the VTP soft robotic design process proposed.

The advantages of viscous thread printing in this application include the ability to create highly customized designs utilizing readily available hardware and materials, with control over component geometry and the ability to precisely tune local mechanical properties as a function of space without extensive post-processing. This method provides a versatile and effective approach to advancing soft robotics.

The soft fingers were modeled after a human finger. The rotational stiffness and range of each joint in a human finger varies from joint to joint and person to person, complicating bio-mimicry. The stiffest joints in a human finger are the proximal interphalangeal (PIP) joints and the distal interphalangeal (DIP) joints of the fingers. These joints, located between the phalanges or segments of the fingers, are critical for finger flexion and extension, allowing the fingers to bend and straighten. The PIP joints are between the first (proximal) and second (middle) phalanges, while the DIP joints are between the second (middle) and third (distal) phalanges. The PIP and DIP joints act similarly to mechanical hinge joints, which maintain greater positional stability and stiffness compared to ball-and-socket joints in the human body (e.g. knee or shoulder). The VTP printed finger structure limits joint movement to a single plane (flexion and extension), by employing a stiff back with high coil density. This results in a desired, high torional stiffness. Other users of VTP for fabricating soft robotic bodies, have used this fact to reduce the significant degrees of freedom in a compliantly deforming body [CITE].

The COMSOL Multiphysics Solid Mechanics module can be used to model the stress and deformation of soft robotic fingers by defining variable zones of stiffness within the finger's structure. By assigning different material properties to regions with varying elasticity or stiffness, engineers can simulate how the finger responds to external forces and actuations. For example, stiffer zones can provide structural support, while softer zones enable greater flexibility and dexterity.

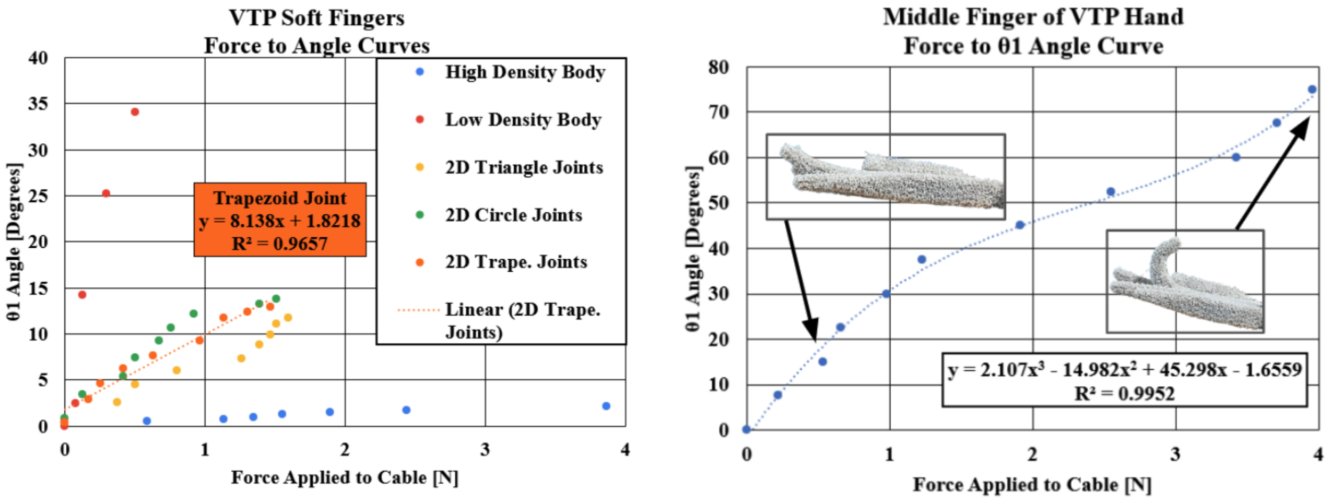

Fig. 5. (A) Viscous thread printing is a method to generate variable density structures with 3D printers. (B) Anatomical terms for the VTP soft fingers. (C) This work is aimed at understanding the force to displacement for a full hand with many degrees of freedom.

COMSOL's ability to incorporate hyperelastic material models allows for accurate simulation of non-linear deformations typical of soft robotics. This enabled the design of VTP soft robotic fingers with tailored mechanical deformation for objects of different internal stiffness regions.

To cable drive the deformation of the VTP joints, a 0.28 mm diameter, nylon fishing line was threaded through loops starting at the base up to the tip of the VTP body. The nylon line was threaded by hand using leather working needle. Due to variability in size and arrangement of coils, nylon cables were attached at intervals of $5mm \pm 1mm$. As the coil diameter decreases, the drag on cables will increase while the distance between attachment points will decrease. Drag forces were found to be less than 10% of the force applied to the finger tip. A FT1117m servo with position feedback was used to apply the pull force. A Pololu motor Maestro controller was used to set the finger to a fixed deformation. At this point, a current measurement was taken to assess how much torque was being applied by the servo. The equivalent tension in the cable was calculated based on the radius of the servo pulley ($0.95cm$). The FT1117M servo operates at a voltage range of 4.8 V to 6.0 V, delivering a torque of approximately 13.5 kg-cm at 6.0V. The servo was used at a speed of $10°/s$ at the 6.0 V. The servo weighs 60 grams while the fingers range in mass from 21.0 grams to 33.3 grams depending on the density and joint shape.

IV. Results

Experimental testing and FEA results shown in Figure 6 show that the displacement of the first joint in the VTP fingers as the cable applied a force to the finger tip. The force to displacement curves are used to quantify the possible regimes of displacement for a soft robotic body with the external dimensions of these VTP fingers. Each experimental and FEA data set was fitted with a third order polynomial trendline.

There were three regimes of deformation found in each finger. The first regime covers initial bending of the finger. The second regime covers plastic buckling of the finger while the gaps in the low density joints are compressed further. The third regime covers concentration of the low density regions into zones of equivalent density to the stiffer, interjoint regions. The circle and triangle jointed fingers were found to have wider, second regime regions in the force to angular displacement plots. The trapezoidal joint geometry fingers balanced the impact of the concentration into the low density region with internal stiffness to reduce the plastic buckling effect. This resulted in an overall more linear response than the other two finger joint shapes.

The joints of a human finger can be thought of as forming a trapezoidal shape because of the way the bones (phalanges) and soft tissues (ligaments and tendons) are arranged. The bones taper slightly at the joint connections, with the wider part at the base (metacarpophalangeal joint) and narrowing toward the fingertip (distal interphalangeal joint). This results in a trapezoidal geometry that provides both stability and flexibility. The ligaments surrounding the joints act like the slanted sides of the trapezoid, allowing for controlled flexion and extension while preventing hyperextension. This anatomical arrangement ensures that the finger can move smoothly and perform precise tasks while maintaining structural integrity.

Each of the two density region VTP fingers were subjected to repeatability testing. A displacement of $\theta_1 = 30°$ was applied once per second for at least one hour. Under this repeated bending, the VTP fingers were found to be robust and the force applied to the cable did not change significantly.

The simulated accuracy results of the soft robotic fingers compared to the experimental results are encouraging and suggest a viable path toward more effective communication aids for the deaf and hard-of-hearing community. With continued research and development, including further testing in

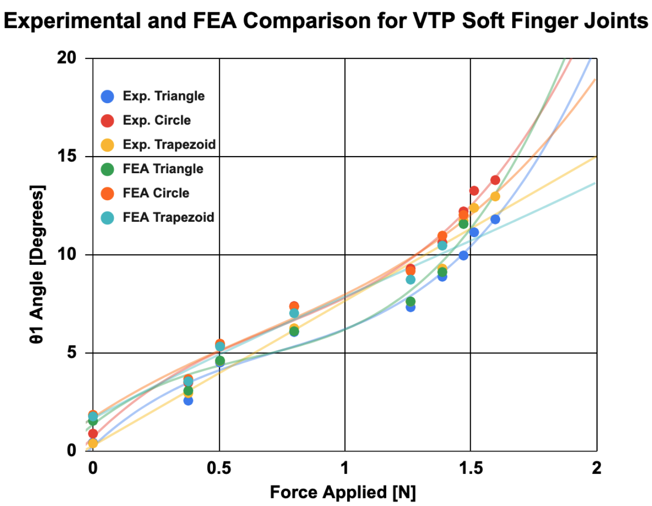

Fig. 6. FEA and experimental data comparison.

real-world conditions, this technology has the potential to improve accessibility. RSS demonstrates how interdisciplinary collaboration can drive innovation for future advancements in assistive soft robotics.

V. Discussion

Prior work into soft robotic gripping has explored pneumatic and cable driven actuation [13] [14].

Prior to FEA modeling, the soft finger bodies were modeled as beams under tension. The deformation of a beam with a point load perpendicular to the normal direction of the beam.

FEA modeling shows that a similar deformation was found for each finger tested. In the FEA model, a set of homogeneous and isotropic material properties were used for each region of variable stiffness. This result means that our method for producing soft robotic bodies is capable of producing bulk regions of homogenity. The low density regions of TPU were set to 0.1 g/cm^3 and the Young's modulus was set to 1.5 MPa.

Fabricating soft robotic bodies with VTP offers scalability benefits, as it can generate intricate foam structures without the need for highly specialized equipment, potentially lowering production costs. By allowing more precise control over the size and distribution of pores, this process may also enhance the material elasticity and load-bearing capacity, addressing issues of mechanical uniformity. Additionally, the use of viscous threads could expand material compatibility, enabling printing with various materials beyond silicone, thus overcoming some environmental or chemical durability limitations. Additionally, the use of viscous threads could expand material compatibility, enabling printing with various materials beyond silicone, thus overcoming some environmental or chemical durability limitations. Hands and fingers were printed on a Mk4 Prusa FFF printer using Ninjaflex TPU. Fingers were produced over 1.45 hrs. These custom prints were produced with one printing nozzle at 30 grams of soft material per hour.

The experimental testing revealed challenges that will be addressed in later work. The surface finish of the VTP bodies is highly variable and dependent on the density of the externally facing region. External dimensions of the test samples varied by up to one coil diameter. Small, single-coil failures along the cable routing path against the front side of the finger. These experiments show the limitations of VTP technology in replicating the full range of organic tissue density required for fluid sign language communication.

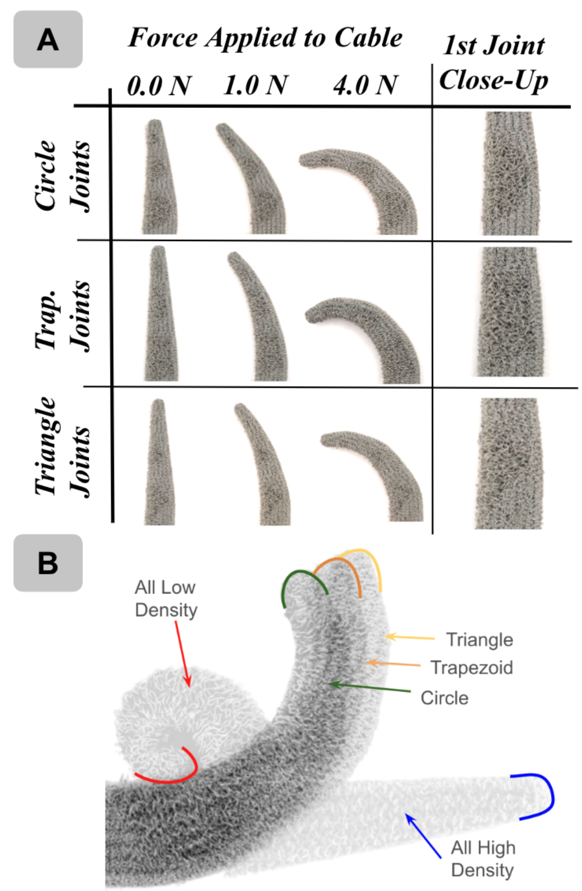

Fig. 7. (A) Snapshots of each three density finger joint type at 0 N, 1 N, and 4 N of force applied to the cable affixed to the outer tip. (B) Overlaid images with semi-opacity, variation in position at 4 N of tension.

VI. Conclusions

The development and testing of these soft robotic bodies to produce a desired deformation pattern demonstrates a framework for advancing soft robotic structures. The testing results demonstrated a a ¡10 % overall difference between modeled and measured material stiffness. The validation of the VTP printed fingers to an FEA model provides confidence in this methodology. While challenges remain, particularly in producing more complex and dynamic shapes with higher variability in density, ongoing refinements in control and slicer design are expected to improve usability and functionality of this technique.

Next steps for work on VTP soft robotic bodies will involve increasing the technical complexity to produce entire hands with designed deformation regimes. The development team plans to fabricate VTP hands and grippers to better generate complex and dynamic symbols, aiming to improve accuracy in producing legible symbols that involve intricate finger positions and fluid movements. This effort will be useful in demonstrating examples of robotic sign language and collaborative, robotic care. Future work will incorporate more advanced control and fabrication techniques. Additionally, the team will explore the incorporation of multi-functional materials in the VTP bodies.

Parallel to these technical improvements, real-world testing of the VTP bodies and user feedback will be integral to the method's evolution. Collaborations with sign language experts may provide valuable insights into the practical usability and effectiveness of these soft fingers and hands to produce legible symbols. The iterative process of testing, feedback, and refinement will ensure that future VTP fabricated, soft robotic bodies are both functional and user-friendly, contributing to greater utility for users of VTP.

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