Pellet Printing for Soft Devices

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Rapid prototyping of soft devices is limited by manual fabrication and additive manufacturing methods that are material-restricted or require extensive post-processing steps. Fused Granulate Fabrication offers a rapid, scalable alternative by extruding thermoplastic pellets through a screw-based extruder directly onto the build surface, enabling continuous, high-throughput printing. FGF also supports the printing of a broad range of materials, from rigid plastics to silicone-soft elastomers (Shore hardness 6A). In this study, we achieved reliable 3D printing of airtight pneumatic soft structures with a volumetric flow rate up to 5 mm^3/s by addressing the root causes of inconsistent extrusion and stringing through hardware, material, and parameter optimizations. We characterized the mechanical performance of thermoplastic styrenic block copolymer pellets, revealing their elastic recovery and Mullins-effect-induced softening. Our additively manufactured pneumatic actuators demonstrated durability over 100,000 bending cycles, which we cross-validated with numerical simulations using Ogden hyperelastic models. We demonstrate a pneumatically actuated robotic hand with 15 individually addressable segments, a multi-chamber robotic fish with an articulated fin, and a soft pressure cuff for blood pressure monitoring. FGF enables the digital fabrication of large (tens of centimeters), airtight, functional soft devices using commercially available thermoplastic pellets, offering a versatile, cost-effective, and scalable alternative to soft lithography with mechanical properties comparable to silicone elastomers.

1 Introduction

Soft robotics is a transformative field that enables the creation of adaptable, compliant, and biomimetic systems [1], with applications spanning medical devices [2], assistive wearables [3], robotic locomotion [4], and manipulation [5], among others. The intrinsic deformability of soft materials enhances safety in human-robot interaction [6], improves resilience to mechanical impact [7], and allows robots to change their shape [8], thereby enabling functionalities beyond the reach of traditional robots with rigid body plans. Despite these advances, the fabrication of soft systems, particularly those requiring airtight properties and materials within the Shore 00 hardness range, remains a major challenge. Soft lithography has long been used to produce such systems, but it involves laborious fabrication steps and depends heavily on operator skill, limiting scalability, reproducibility, and broader adoption beyond specialized laboratories [9]. As a result, many state-of-the-art demonstrations, including multi-gait soft robots [8], bistable valves [10], and soft grippers [11], still rely on custom molds, extensive post-processing, and manual assembly.

Digital fabrication techniques including Fused Filament Fabrication (FFF), Direct Ink Writing (DIW), Stereolithography (SLA), Material Jetting (MJ), and Selective Laser Sintering (SLS), have been explored as mold-free alternatives to soft lithography for fabricating soft devices. However, each method presents fundamental trade-offs in material compatibility, geometric fidelity, and printing reliability that have limited their widespread use [12, 13, 14]. While FFF remains popular due to its low cost and accessibility [15, 16, 17, 18, 19, 20, 21, 22, 23], its performance is constrained by filament mechanics. Commercial soft filaments are typically thermoplastic polyurethanes (TPUs) with Shore hardness $\geq$ 60A, which are relatively stiff compared to silicones and often lead to extrusion issues such as buckling and jamming during printing [24]. DIW allows printing of silicones and hydrogels at lower Shore hardness levels but requires rheological tuning and curing steps, resulting in a slow, process-sensitive fabrication strategy [25, 26, 27, 28, 29, 30]. SLA and MJ offer high print resolution but rely on brittle photopolymers with viscoelastic material characteristics, poor fatigue resistance, and UV degradation [31, 32, 33]. SLS avoids support structures but is limited by challenges in powder removal and a narrow range of available soft elastomers ($\geq 40A$). Although these techniques have enabled important advances in soft device manufacturing, their material and process constraints continue to limit the geometric complexity, mechanical performance, and reproducibility of fabricated devices. These challenges become more severe in fluidically driven soft systems, where airtightness and geometric precision are essential for integrating channels and enclosed chambers within a single build. SLA, MJ, SLS, and DIW struggle with internal cavities where residual resin, powder, or ink becomes trapped, especially in long, narrow channels and complex internal networks [34, 35]. Although MJ supports the use of support materials, their removal still hinders the fabrication of fully enclosed chambers. FFF methods mitigate this issue but introduce their own challenges including leakage and limited print reliability for complex geometries. 3D printing airtight structures reliably requires slow print speeds (<20 mm/s) and restrictive design rules, such as multi-layered walls [18] or Euler-path toolpaths to minimize interfacial voids [22]. Other strategies to improve airtightness include gravity-assisted layer sealing [36] and vision-based closed-loop control for real-time defect correction [24]. Although FFF has become more reliable for fabricating soft devices, it remains fundamentally limited in material selection, as it can only print materials with high Shore hardness, far from the low hardness characteristic of silicones.

A promising alternative to established printing strategies is Fused Granulate Fabrication (FGF). FGF has been primarily used in industry rather than in research laboratories. It offers several industry relevant advantages including high throughput, low material cost, broad material availability, existing expertise from injection molding, and the capability to print at large scales. FGF processes raw pellets through an extrusion screw, achieving higher extrusion rates and access to a wider range of thermoplastics than FFF [37, 38]. Thermoplastic styrenic block copolymers (TPS) can achieve lower Shore hardness values than other classes of thermoplastic elastomers (TPEs) [39]. Previous studies have used desktop FGF printers to demonstrate their potential for printing specialized materials [40, 41], including conductive pellets for sensorized actuators [39, 42, 43] and ultra-soft membranes within the Shore 00–30 range [44]. However, these efforts have been isolated, with limited exploration of geometry and material diversity [43, 44, 41], leaving much of the thermoplastic elastomer landscape across the Shore 00 and A scales unexamined. Although many thermoplastic pellets exist with Shore hardness values comparable to silicones, their suitability for desktop printing remains largely unknown. Most thermoplastic pellets are formulated for injection molding rather than for additive manufacturing. The relationship between material rheology, mechanical properties, and print fidelity in FGF is not yet well studied, making it unclear which parameters most strongly affect print reliability. We need a systematic evaluation and benchmarking of key performance metrics including elasticity, strain softening, fatigue resistance, and processability, to establish the potential of thermoplastic pellets as next-generation materials for soft devices. In contrast to FFF printers and filaments, which have matured with well-defined process parameters, FGF remains at an early stage of technological development.

Commercially available pellet extruders and compatible desktop 3D printers are limited. The few reported FGF systems rely on custom-built extruders, which reduces reproducibility and hinders standardization [41, 44]. The high extrusion rates typical of pellet extruders, while beneficial for throughput, increase the likelihood of print defects. Severe stringing has been observed in FGF-printed pneumatic actuators [41]. Hardware modifications to the 3D printer such as custom needle valves have been proposed to reduce oozing, but these solutions have not been broadly tested with different materials and are difficult to reproduce [45]. Only a few studies have demonstrated mechanically complex geometries. Large-scale, fluidically driven soft devices have remained mostly unexplored. As a result, the capability of FGF to reliably fabricate high-quality soft devices remains uncertain and has not yet achieved widespread adoption within the soft robotics community or beyond.

In this study, we address the challenges of FGF and demonstrate the feasibility of using a desktop printer to fabricate large, geometrically complex, fluidically driven soft devices. Through systematic testing and iterative refinement of the print head, material selection, and process parameters, we resolved the primary failure modes that limit airtight fabrication, including inconsistent extrusion and stringing. By identifying effective parameter combinations, we successfully printed TPS pellets with Shore hardness values from 6A (00–55) to 50A (00–85) while maintaining higher flow rates than both FFF and DIW (Figure 1). Stringing was effectively mitigated by discovering material options with high viscosity and strong shear-thinning behavior. Our refined print head, selected materials, and optimized print parameters enable the broader adoption of FGF in soft device manufacturing.

To evaluate the suitability of TPS materials for fabricating soft devices, we characterized their mechanical properties through tensile testing. We 3D printed pneumatic actuators, measured their bending response, and compared the results with numerical simulations. Fatigue testing confirmed actuator durability beyond 100,000 actuation cycles. Tensile cycling and actuator bending experiments revealed a pronounced reduction in Young's modulus after the first stress cycle. This observation is attributed to the Mullins effect and emphasizes the need to activate the printed device once before it is used in operation. We demonstrated the versatility of FGF by 3D printing a pneumatically driven soft hand with 15 individually addressable segments, a multi-chamber robotic fish with an articulated fin, and a pressure cuff for measuring systolic pressure. This study shows that FGF provides a robust, accessible, and cost-effective method for rapidly prototyping large soft devices (tens of centimeters). With tens of thousands of thermoplastic pellets commercially available, including materials with silicone-like softness, FGF unlocks a broad and previously inaccessible material palette for applications in robotics, medical devices, wearables, and beyond.

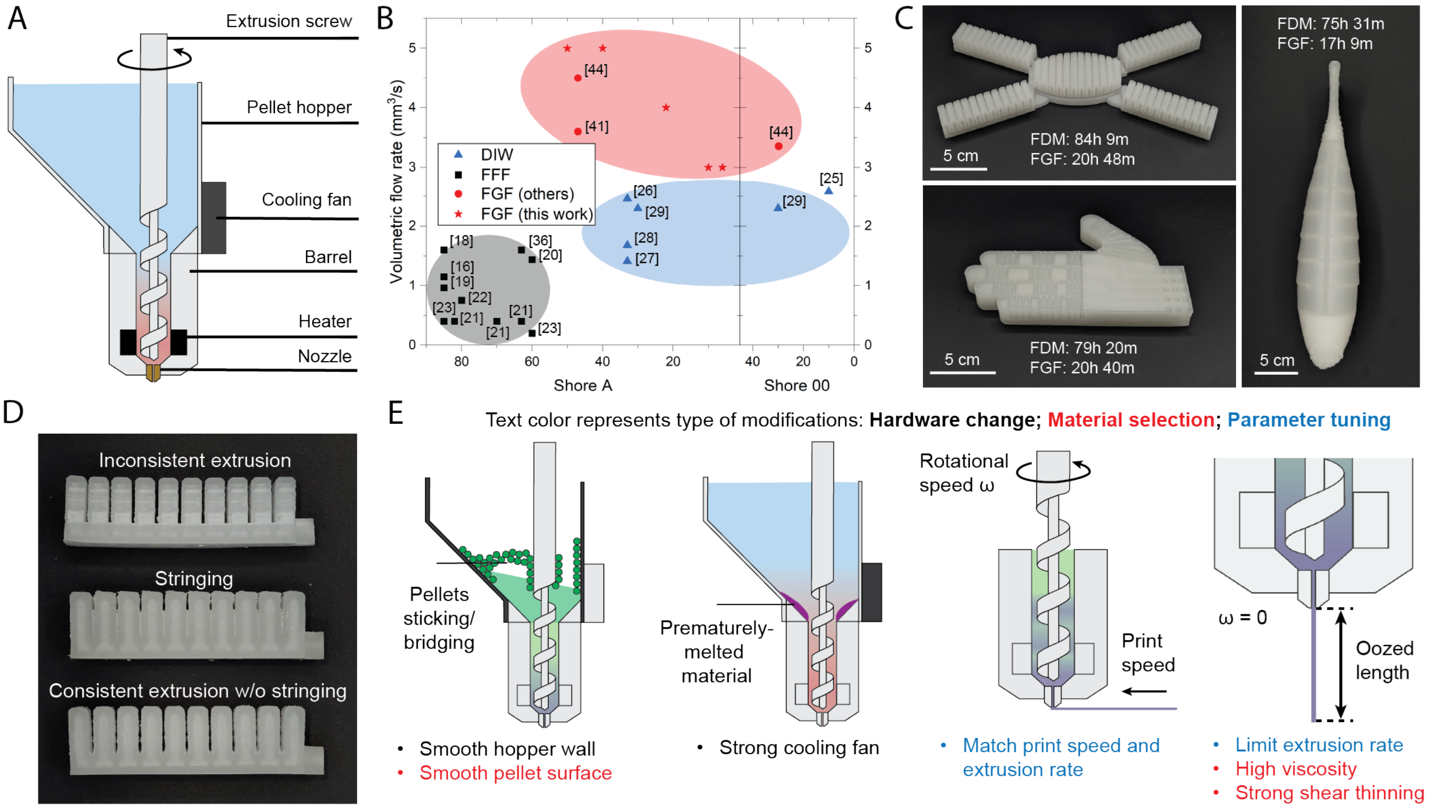

Figure 1: **Overview of the Fused Granulate Fabrication (FGF) printing process.** (A) Schematic of pellet extruder. (B) Estimated volumetric flow rate versus Shore A hardness from prior FFF and FGF studies on airtight soft robot fabrication, highlighting that FGF achieves higher volumetric flow rates while supporting softer materials than FFF. (C) Example of large-scale complex geometries printed with FGF, demonstrating that FGF significantly accelerates the fabrication of large soft structures. Print parameters are summarized in Supporting Information, Table S2. (D) Images of printed pneumatic actuators highlighting two common defects, inconsistent extrusion and stringing, that can compromise functionality, alongside an optimized print demonstrating successful mitigation through tuning. (E) Causes and solutions we implemented for inconsistent extrusion and stringing issues.

2 Pellet printing with soft materials

FGF, or pellet printing, operates on the same layer-by-layer deposition principle as FFF but uses thermoplastic pellets instead of filament feedstock. Pellets are fed by gravity or pneumatics into a screw-driven extruder, where they are melted and deposited through a heated nozzle (**Figure 1A**). This screw-based extrusion decouples material rigidity from processability, enabling the reliable printing of soft thermoplastic elastomers with stiffness comparable to silicones. In contrast, filament-fed FFF systems are prone to buckling when processing soft materials. To quantify this advantage, we analyzed published studies reporting airtight soft robotic components fabricated via DIW, FFF, or FGF. Volumetric flow rates Q (mm^3/s) were estimated from reported nozzle diameters d (mm), layer heights h (mm), and print speeds v (mm/s) using their relation $Q = d \times h \times v$, assuming the extrusion width equals the nozzle diameter. The resulting comparison of volumetric flow rate versus material Shore hardness shows that FGF consistently achieves higher flow rates, even for softer materials (**Figure 1B**). FGF reduced the fabrication time of our demonstrators from several days using FFF to a single day (**Figure 1C**). While FGF offers several advantages over FFF including higher flow rates and broader compatibility with soft materials, it remains challenging to achieve consistent, high-quality prints. To promote the broader adoption of FGF for fabricating soft devices, we used a commercially available pellet extruder, a standard 3D printer, and commercially available soft thermoplastic pellets in our experiments. Although small, flat structures can be fabricated reliably, longer print durations and increased structural complexity lead to recurring issues such as mid-print failures, leakage, and stringing. We identified two main causes of these defects: inconsistent extrusion and stringing (**Figure 1D**). Severe occurrences of either can result in complete print failure, while milder cases compromise airtightness and device performance. Overcoming these challenges requires a coordinated strategy combining hardware modifications, material selection, and process parameter optimization (**Figure 1E**).

2.1 Enabling consistent extrusion

Inconsistent extrusion leads to non-uniform wall thickness, which can cause leakage in under-extruded regions or require higher actuation pressures in over-extruded areas of the printed soft device. We mitigated this issue through a three-step approach addressing feeding, melting, and extrusion: (1) improving pellet feeding by redesigning the print head hopper with smoother walls and selecting pellets with low surface friction; (2) preventing premature melting by enhancing active cooling using a higher performing fan; and (3) calibrating extrusion flow to match print speed, ensuring consistent material deposition. Further details on these improvements are provided in the Supporting Information Section 2.1.

2.2 Reducing stringing

Stringing refers to the formation of unintended thin strands of thermoplastic between printed features, caused by residual oozing during the non-print travel of the print head. Even after the extrusion screw stops rotating, molten material can continue to ooze due to gravity and residual back pressure within the barrel. This effect is especially pronounced in soft, elastic materials and can lead to geometric distortions, internal voids, and ultimately leakage or reduced device performance. In FFF, stringing is typically mitigated through filament retraction; however, applying retraction to elastomers often introduces extrusion instability. In contrast, FGF offers access to a broader range of pelletized materials, enabling material selection as an effective strategy for minimizing stringing. To explore this strategy, we evaluated three types of TPE pellets (Filaflex 60A, Baiyu 30A, and TF2ATL 22A) through oozing and extru-

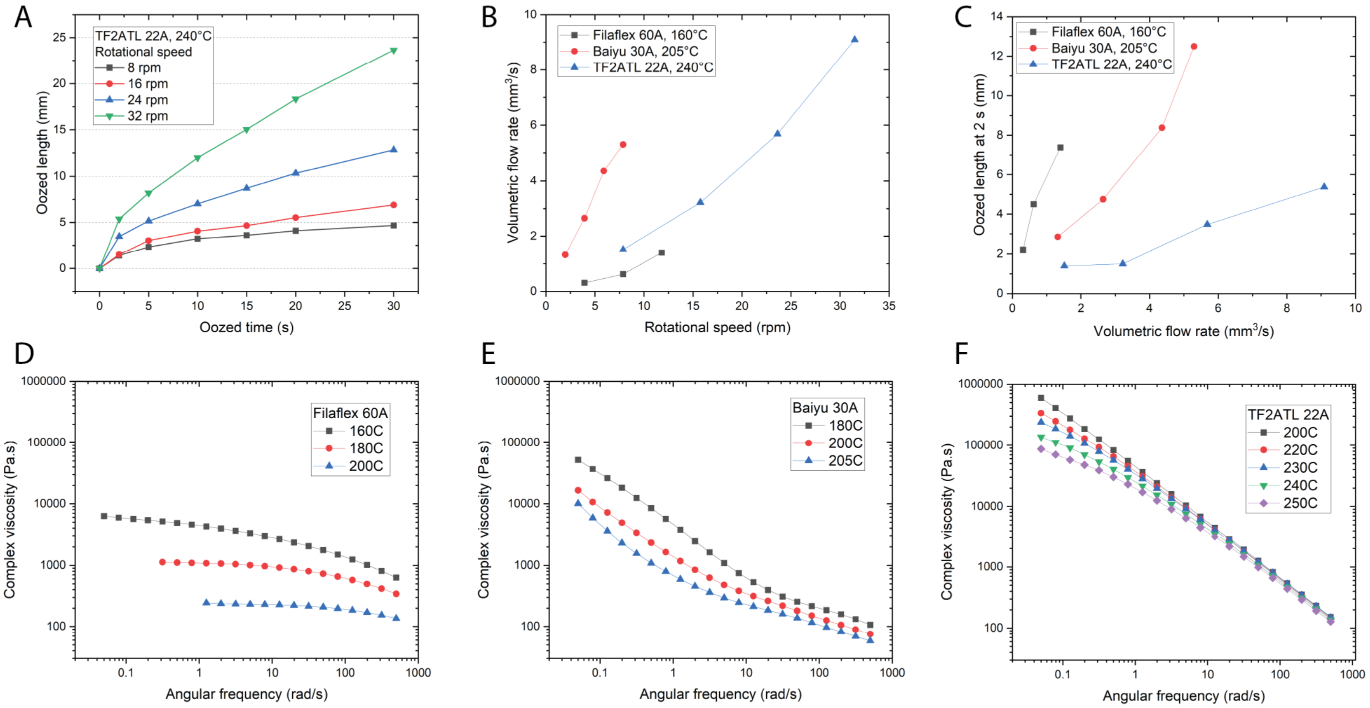

Figure 2: **Extrusion and rheology characterization of TPE pellets.** (A) Oozed length (Figure 1E) versus time for pellets with a Shore hardness of 22A at a temperature of 240 °C under different rotational speeds of the extrusion screw (Figure 1A). (B) Volumetric flow rate as a function of rotational speed of the extrusion screw for different pellets at their respective print temperatures. (C) Oozed length after 2 seconds versus volumetric flow rate for different materials at their respective print temperatures, showing that at the same volumetric flow rate, the 22A material exhibits significantly less oozing than the other two materials. (D-F) Complex viscosity as a function of angular frequency at different temperatures for different pellets (D) 63A pellets from Recreus, (E) 30A pellets from Yangzhou Baiyu, and (F) 22A pellets from Kraiburg TPE GmbH.

sion experiments and rheological characterization. We note that Filaflex 60A is the commercial name of the material, while the manufacturer's datasheet specifies its Shore hardness as 63A.

The oozing tests revealed that the length of extruded material increased with both time and the rotational speed of the extrusion screw (**Figure 2A**, **Movie S1**). Similarly, extrusion tests revealed that the volumetric flow rate increased with rotational speed for all three materials (**Figure 2B**). While high flow rates are desirable for faster printing, they must be carefully controlled to minimize oozing. When we plotted the oozed length against the corresponding volumetric flow rate, we found that TF2ATL pellets exhibited consistently lower oozing across the tested range compared with the other two materials (**Figure 2C**). Rheological characterization further clarified the mechanisms responsible for these differences in printing behavior. Filaflex 60A pellets, a commonly used soft TPU with a recommended FFF printing temperature of 235 °C, exhibited severe oozing in the FGF system even at 160 °C and low flow rates. This result aligns with its relatively low viscosity and weak shear-thinning behavior, which permit continued flow after screw rotation ceases (**Figure 2D**). In contrast, Baiyu 30A and TF2ATL 22A pellets exhibited higher viscosities at low shear rates, with TF2ATL showing both consistently higher viscosity across the frequency spectrum and more pronounced shear-thinning behavior (**Figure 2E,F**). Although reducing the print temperature of Baiyu 30A increased viscosity and decreased oozing, it also weakened interlayer adhesion, compromising print reliability. In comparison, the viscosity–frequency response of TF2ATL showed minimal temperature dependence, enabling the use of higher processing temperatures to improve layer bonding without increasing oozing. These results indicate that selecting materials with high low-shear viscosity and strong shear-thinning behavior, combined with careful tuning of process parameters, provides a simple and very effective strategy for achieving consistent, airtight prints in FGF-based fabrication of soft devices.

3 Material characterization

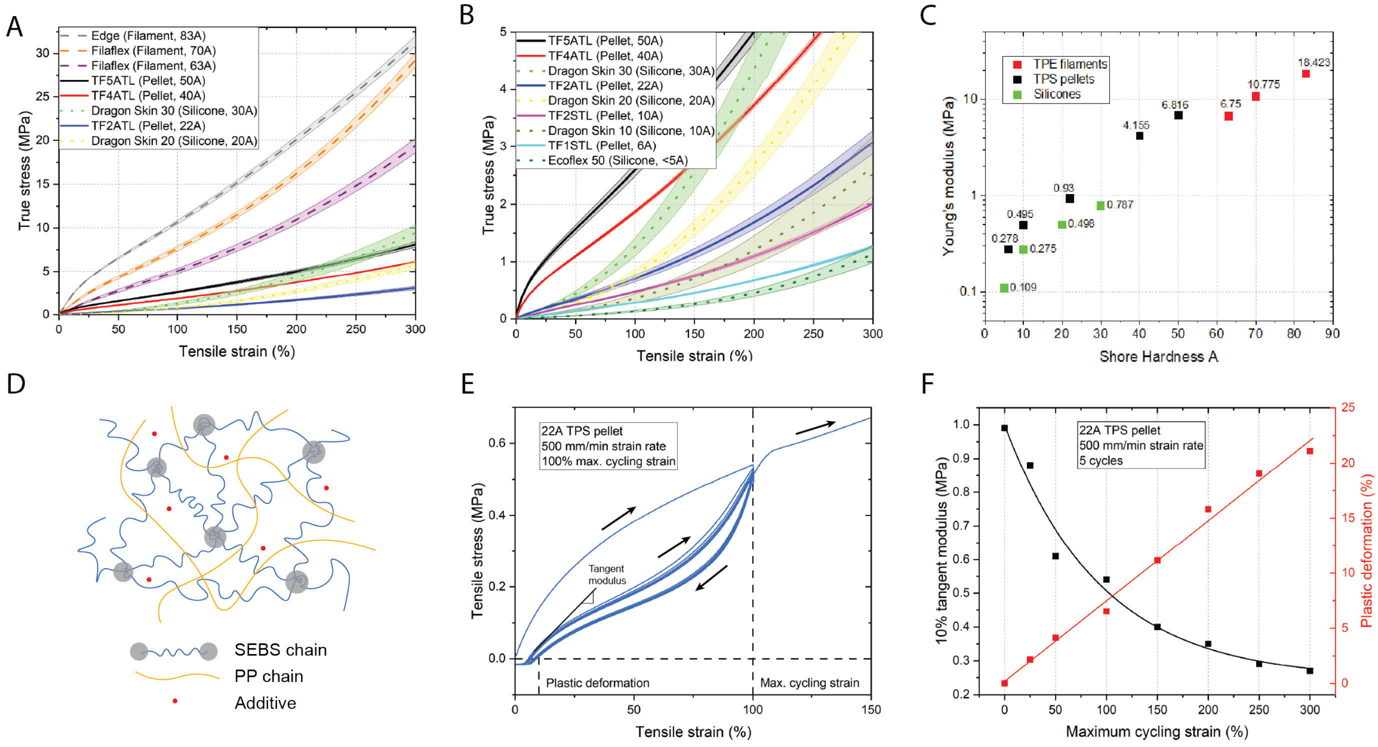

Figure 3: **Mechanical characterization of TPE filaments, TPS pellets, and silicone materials for soft structure fabrication.** (A) True stress–strain curves up to 300% strain, with shaded 95% confidence intervals from five tests. (B) Zoomed-in view highlighting stress-strain response of materials with lower Young's modulus. (C) Young's modulus versus Shore hardness, showing the correlation between stiffness and hardness. (D) Microstructure of a SEBS–PP blend TPS material. PP is commonly incorporated into TPS formulations to tune elasticity and processability. (E) Representative tensile cycling test on 22A TPS pellets, illustrating loading–unloading behavior, tangent modulus, and plastic deformation. (F) Effect of maximum cycling strain on 10% tangent modulus and plastic deformation for 22A pellets.

To guide our material selection and better understand the behavior of printed structures, we characterized representative TPE filaments, TPS pellets, and silicone rubbers. Five dogbone specimens per material were prepared using FDM printing, FGF printing, and molding in accordance with ASTM D412 and tested under uniaxial tension. We converted the engineering strain to true strain to more accurately capture nonlinear behavior at low strain, and plotted stress-strain curves up to 300% strain along with 95% confidence intervals for each material (**Figure 3A**). Our results show that TPE filaments exhibit high stiffness and strain softening within the first 100% strain, reflecting their high initial modulus and limited extensibility. In contrast, TPS pellets displayed substantially lower stiffness. Softer pellets, particularly those with Shore hardness below 22A, exhibited low modulus and minimal initial softening, showing mechanical behavior comparable to commercial silicones (**Figure 3B**). The observed correlation between Young's modulus and Shore hardness confirms the general trend of increasing stiffness with Shore hardness and demonstrates the wider modulus range achievable with TPS pellets (**Figure 3C**). Commercial TPS pellets contain not only SEBS but also polypropylene (PP) (**Figure 3D**). PP helps tune the elasticity and processability of TPS materials but also contributes to a more pronounced Mullins effect, an irreversible stress-softening observed in elastomers after the first loading cycle. To evaluate elastic recovery and fatigue behavior, we conducted cyclic tensile tests on samples fabricated from 22A TPS pellets at a strain rate of 500 mm/min with incremental strain limits. The loading–unloading curve of the 22A material reveals a reduction in tangent modulus and the presence of permanent plastic deformation (**Figure 3E**). Most mechanical degradation occurs during the first cycle, after which subsequent cycles show more stable behavior (**Supporting Information, Figure S4A**). Increasing the maximum strain leads to a monotonic rise in plastic deformation and a corresponding decrease in the 10% tangent modulus (**Figure 3F**).

4 Case study: Pellet printed pneumatic actuators

4.1 Mechanical characterization of pellet printed PneuNets

To evaluate the performance of soft devices fabricated via FGF, we designed, printed, and tested a pneumatic network (PneuNet) actuator using TPS pellets of varying Shore hardness. Actuation performance was evaluated by measuring the bending angle as a function of input pressure (**Figure 4A**) and comparing the results with silicone-molded and filament-printed PneuNet actuators (**Supporting Information, Figure S5**).

To assess long-term durability, we subjected the 22A actuator to continuous operation for up to 100,000 actuation cycles (**Figure 4B**). The pressure–bending relationship remained consistent throughout testing, showing minimal degradation in peak angle or response behavior. These results confirm that soft actuators fabricated via FGF maintain airtightness and mechanical integrity under extended use. A distinct change between the first and second cycles reflects the Mullins effect, which stabilizes thereafter and does not compromise long-term functionality. The Mullins effect observed in 3D-printed TPS structures can be viewed as a form of mechanical conditioning, during which the actuator reaches its steady-state performance.

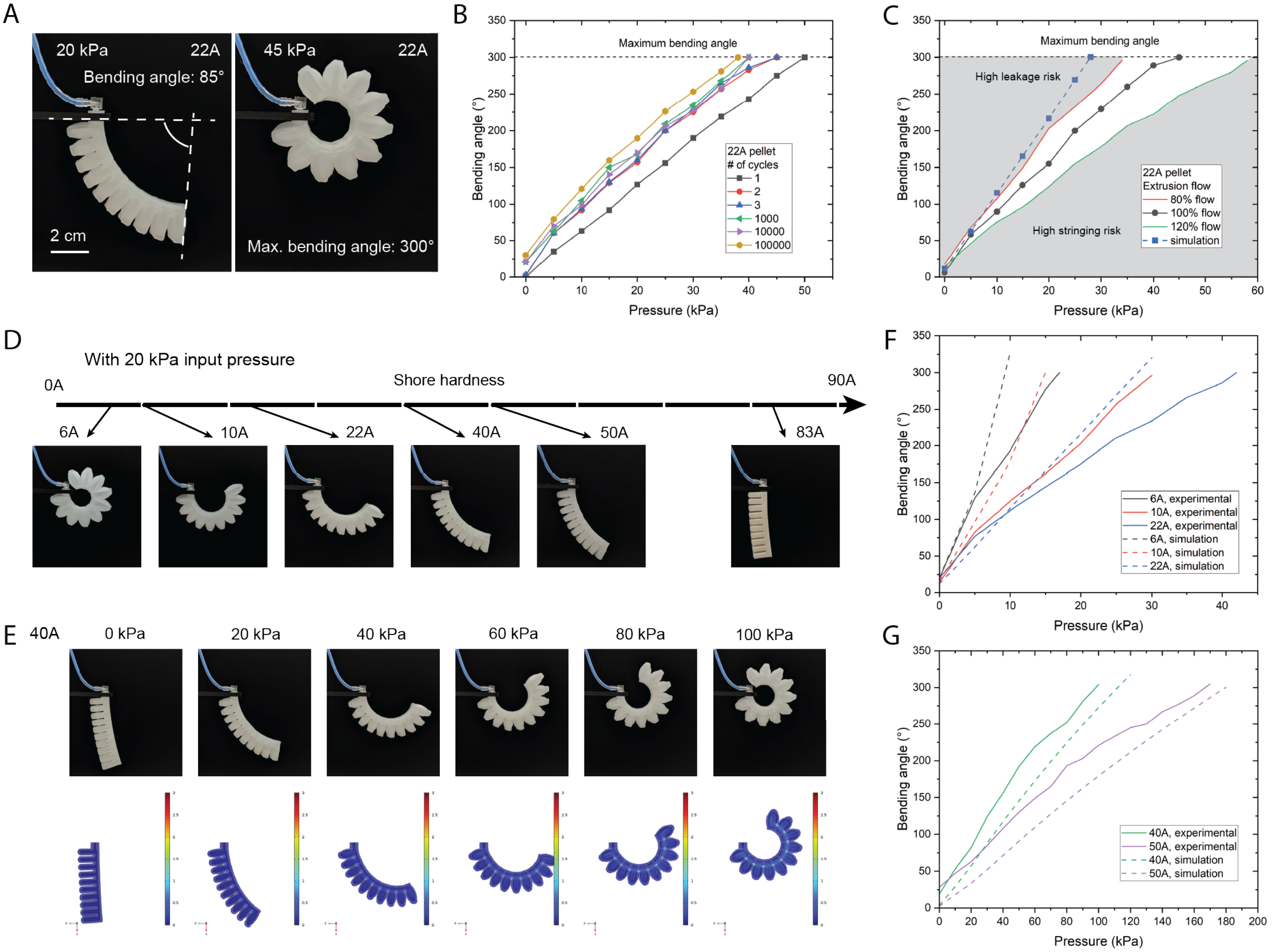

Figure 4: **Characterization of soft actuators printed with TPS pellets using FGF.** (A) PneuNet actuator fabricated from 22A pellets, illustrating bending angles of 85 °and 300 °at maximum deformation. (B) Bending angle as a function of pressure measured over 1–100,000 actuation cycles, demonstrating stable and repeatable actuator performance. (C) Effect of extrusion flow rate on actuator bending behavior; shaded regions denote operating conditions associated with leakage and stringing. The flow percentage indicates the relative setting with respect to the recommended flow rate for the 22A pellet and does not represent the absolute volumetric flow rate. (D) Comparison of actuator bending at 20 kPa for materials with varying Shore hardness, illustrating the influence of material stiffness on deformation performance. (E) Experimental and simulated deformation profiles of a 40A actuator under increasing pressure, highlighting the agreement between measured and predicted bending behavior. (F) Bending angle as a function of pressure for 6A, 10A, and 22A actuators, showing reduced experimental bending compared to simulations due to over-extrusion effects during fabrication. (G) Comparison of bending angles for 40A and 50A actuators, with discrepancies between experimental and simulated results attributed to the Mullins effect and material stress softening.

We further examined the effect of extrusion flow rate on actuator performance (**Figure 4C**). Under-extrusion resulted in poor interlayer adhesion and leakage, while over-extrusion caused stringing and geometric distortion. By fine-tuning the flow rate, we achieved reproducible fabrication of airtight actuators with consistent bending behavior. However, Finite Element Analysis (FEA) aligned more closely with the response of under-extruded actuators, suggesting that the over-extrusion typically used to ensure airtightness causes deviations between experimental and simulated performance.

We investigated the material-dependent mechanical response of pneumatic actuators by fabricating PneuNets using FGF with TPS pellets spanning Shore hardness values from 6A to 50A (**Figure 4D**). Under identical input pressures, softer materials produced significantly greater deformation due to their lower elastic modulus and higher compliance. In contrast, a PneuNet printed via FFF using a commercial TPU filament (Ninjaflex Edge, 83A) exhibited minimal bending. This result highlights the importance of 3D printable materials with Shore hardness comparable to silicones, which here enable large deformations in soft pneumatic actuators.

4.2 Numerical simulation of PneuNet bending behaviors

To gain deeper insight into actuator performance and evaluate the accuracy of our simulations, we conducted FEA using material models calibrated with uniaxial tensile test data. For each material, a hyperelastic constitutive model was fitted to capture nonlinear deformation behavior, and the pressurization-induced response of the PneuNet actuators was simulated. The resulting simulated deformations were then compared with experimental measurements to evaluate the fidelity of the model.

The simulated deformation profiles showed strong agreement with the experimentally observed bending shapes, confirming that the fitted material models accurately captured the overall deformation behavior (**Figure 4E**). However, systematic discrepancies were evident in the pressure–bending angle relationships across different materials.

For actuators fabricated from 6A, 10A, and 22A TPS pellets, the experimentally measured bending angles were consistently lower than those predicted by the numerical model (**Figure 4F**). This discrepancy is likely due to over-extrusion during printing, which increased wall thickness and overall stiffness—factors not represented in the idealized numerical model. In contrast, actuators printed with 40A and 50A pellets exhibited bending angles exceeding the simulated predictions (**Figure 4G**). This deviation is attributed to the Mullins effect, a stress-softening phenomenon not captured by the material models, which becomes more pronounced in stiffer elastomers subjected to large strains.

These comparisons highlight the importance of studying fabrication-induced variability and time-dependent viscoelastic effects to improve the predictive accuracy of computational models for soft pneumatic actuators.

5 Demonstrations

5.1 Soft robotic hand

We designed, fabricated, and tested a fully soft robotic hand to demonstrate the capability of FGF to produce complex, integrated fluidic devices. Printing the hand with 22A pellets required 20 hours and 40 minutes (**Movie S2**). The hand consists of five fingers, each containing three independent embed-

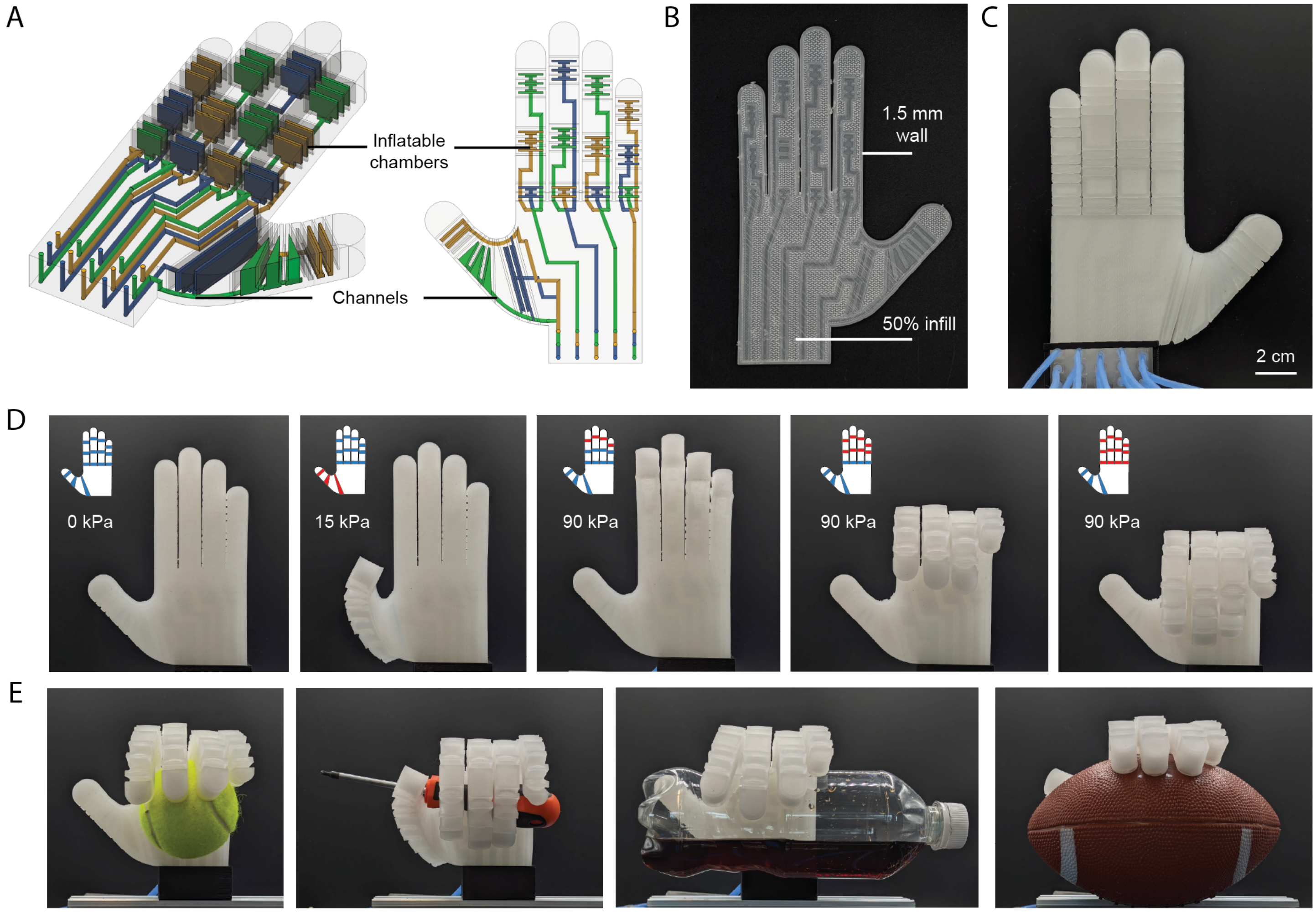

Figure 5: **Robotic hand demonstrating reliable FGF printing of a complex fluidic device.** (A) Semi-transparent CAD rendering of the hand design, with blue, yellow, and green regions indicating internal channels and inflatable chambers. (B) Close-up image of the printed hand at a 3 mm layer height, showing thin-wall structures, internal channels, and 50% gyroid infill. (C) Image of the backside of the printed hand. (D) Actuation sequence illustrating the transition from the extended to fully grasping state through sequential activation of chambers in the fingers and thumb. Hand schematics in the top left corner indicate actuator status, with red denoting actuated and blue representing unactuated chambers. (E) Demonstration of the robotic hand grasping a variety of everyday objects.

ded pneumatic chambers connected through integrated fluidic pathways (**Figure 5A**). The structure was printed monolithically, without any post-processing or assembly. Thin outer walls (1.5 mm, three perimeters) and a 50% gyroid infill were used to balance compliance and airtightness (**Figure 5B**). All inflatable chambers connect to internal channels that merge at the back of the hand within a compact routing manifold, allowing 15 individual tubes to deliver pressurized air to each chamber for actuation (**Figure 5C**). Sequential actuation of these chambers enables coordinated bending across the finger segments, culminating in a full grasping configuration (**Figure 5D**). The robotic hand successfully grasped objects of varying sizes and geometries (**Figure 5E**, **Movie S3**), demonstrating the effectiveness of FGF in fabricating functional, monolithic soft robotic systems with intricate internal channel networks.

5.2 Soft robotic fish

We fabricated a soft robotic fish using FGF to evaluate the airtightness and structural integrity of monolithically printed components for underwater applications. The design was intentionally developed to

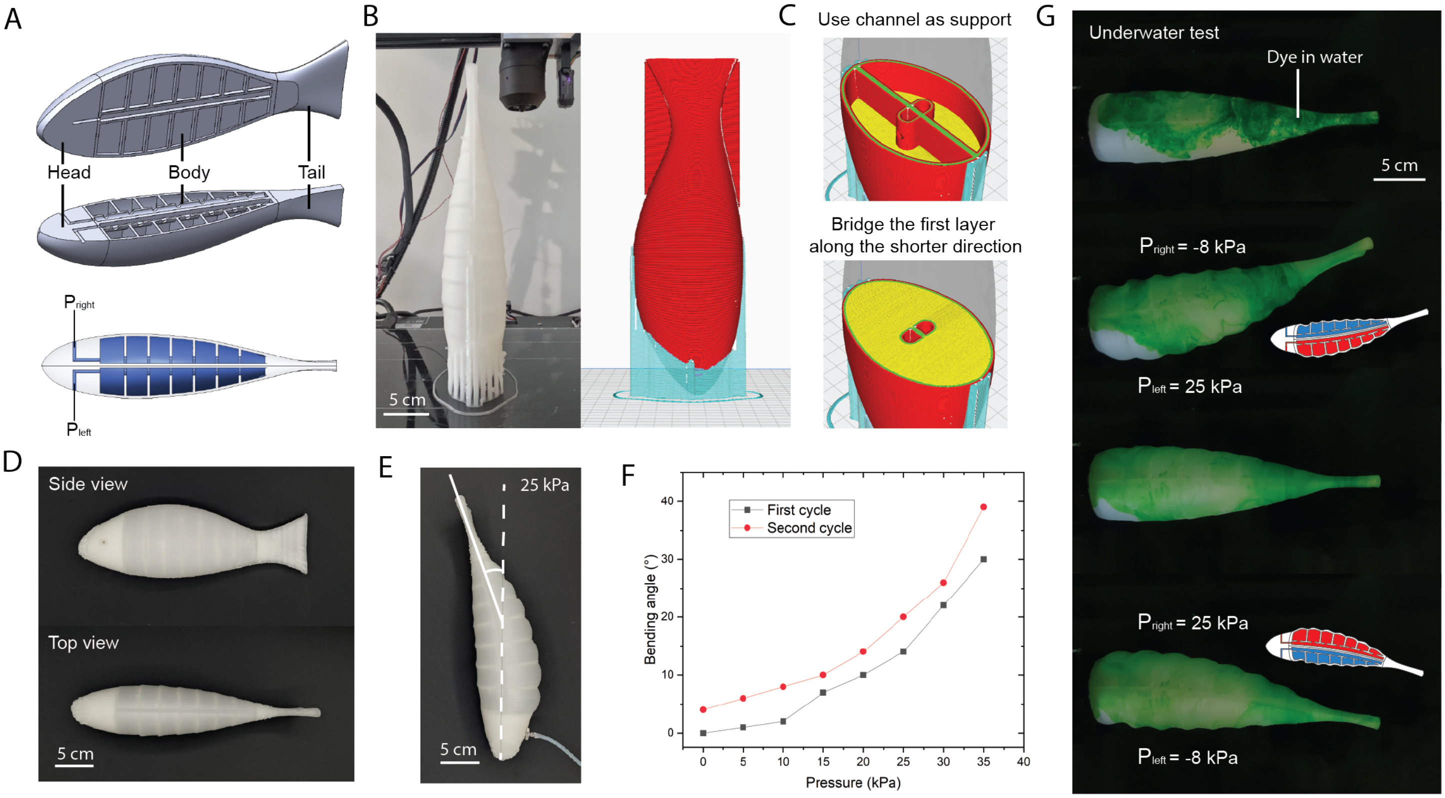

Figure 6: **Robot fish demonstrating airtight print for underwater applications.** (A) Cross-sectional CAD view of the robotic fish design and schematic of the two-chamber actuation principle. (B) Slicer view (right image) of the fish model (blue regions indicate support material) and photograph of the printed part (left image) in its final state. (C) Design principle for long bridges. (D) Photographs of the printed fish from side and top views. (E) Photograph of the robotic fish bending during actuation of its left chamber (right side from the viewer's perspective) at 25 kPa, with the bending angle measurement indicated. (F) Bending angle as a function of input pressure over two actuation cycles. (G) Underwater images of the actuated robotic fish demonstrating full airtightness and periodic tail-swinging motion.

demonstrate the feasibility of printing tall, geometrically complex structures with extended bridges and overhangs. Such features remain difficult to achieve with conventional FDM-fabricated soft systems, which are generally constrained to low-profile architectures. The robot consists of three sections: head, body, and tail (**Figure 6A**). They can be printed using 22A TPS either as separate parts assembled post-printing or as a single monolithic structure with support material.

Monolithic printing with support material required 17 hours and 9 minutes (**Figure 6B**, **Movie S4**). The body section houses all pneumatic chambers, featuring 2 mm-thick outer walls (four perimeters) and bridges exceeding 10 mm in length. A central spinal structure was added to distribute airflow and support bridges during printing. To enhance print reliability, all first-layer bridges were oriented along their shorter span, and travel speed was reduced to 100 mm/s to limit vibration, especially when printing taller sections (**Figure 6C**). The actuator architecture comprises two independent pneumatic chambers located on the left and right sides of the body. Differential pressurization of these chambers induces lateral bending of the body and tail. The bending angle at identical input pressures increased after the first activation cycle, consistent with Mullins-type stress softening (**Figure 6E, F**). During underwater testing, the robotic fish remained airtight throughout repeated actuation cycles (**Figure 6G**, **Movie S5**).

5.3 Wearable pressure cuff

We demonstrated the fabrication of wearable pneumatic devices by 3D printing a soft pressure cuff with embedded inflatable chambers using 50A TPS pellets. The design featured a single-layer thin inner wall

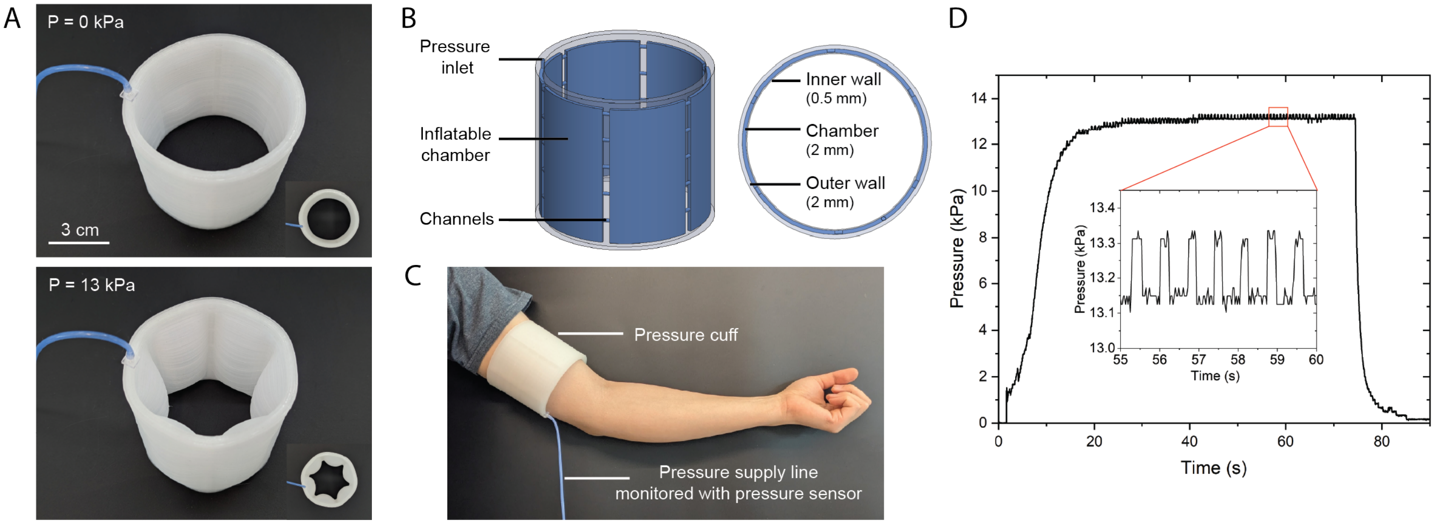

Figure 7: **Pressure cuff demonstrating wearable applications.** (A) Photographs of the printed cuff in unpressurized (0 kPa) and pressurized (13 kPa) states. (B) CAD model and cross-sectional view of the pressure cuff, with blue regions showing the internal inflatable chambers and channels. (C) Demonstration of the cuff worn on an arm. (D) Pressure profile during inflation, with inset showing high-frequency pressure fluctuations from the heartbeat.

and a thicker outer wall, with interconnected chambers enabling uniform pressurization (**Figure 7A**). The cuff was printed monolithically in 9 hours and 26 minutes. Upon inflation through a single inlet, the asymmetric wall geometry caused the thinner inner wall to bulge inward, generating radial compression around the limb (**Figure 7B**). The geometry was optimized to operate within standard blood pressure ranges (11.3–17.3kPa), providing a balance between compliance and stiffness. Compared to the 22A pellets used in other demonstrations, the 50A material offered improved mechanical stability while maintaining sensitivity to modest pressure variations. Despite its thin-wall design, the cuff remained fully airtight, underscoring the reliability of the FGF extrusion process. When applied to the upper arm, the device generated uniform radial pressure and enabled systolic pressure measurement via an external pressure sensor (**Figure 7C,D**). The cuff maintained stable internal pressure across repeated actuation cycles, and the presence of high-frequency pressure oscillations in the recorded signal confirmed both the airtightness of the chambers and the mechanical responsiveness of the structure to dynamic loading conditions (**Figure 7E**).

6 Discussion

FGF provides access to a vast and largely untapped library of thermoplastic materials from the established polymer industry, including hydrophobic, conductive, biodegradable, and recycled formulations. This versatility enables designers to expand the functional scope of 3D-printed soft devices by tailoring material properties to specific application requirements. By facilitating the use of diverse thermoplastics with tunable mechanical, electrical, and chemical characteristics, FGF supports application-specific customization and scalable manufacturing, enabling new designs and use cases beyond the reach of traditional filament-based approaches.

Each new material, however, necessitates dedicated evaluation of its printability and the performance of the resulting structures. The present work introduces a systematic framework and workflow for tuning and characterizing materials, establishing a foundation for future exploration (**Supporting Information, Section 4**). To further broaden the accessible material space, it will be essential to identify and define material requirements suited for FGF, such as high viscosity and pronounced shear-thinning behavior to minimize oozing and enhance print fidelity. These criteria can guide the formulation of new thermoplastic blends specifically optimized for the rapid fabrication of high-quality soft devices.

Looking ahead, enabling multimaterial FGF will make it possible to fabricate complex, gradient, or functionally segmented soft robots within a single print, combining materials of similar chemistry but differ-

ing stiffness, conductivity, or permeability in one monolithic structure. This approach will also address current limitations in printing overhangs and bridges by using dissolvable or sacrificial support materials, enabling more advanced designs and improved performance in next-generation soft robotic systems.
Beyond fabrication, the stress-softening associated with the Mullins effect can be deliberately exploited as a design feature, where the initial inelastic deformation is used to program application-specific mechanical responses.

7 Conclusion

A comprehensive experimental framework was developed, encompassing mechanical characterization of TPS materials, quantification of the Mullins effect, and evaluation of pneumatic actuator durability and bending performance supported by finite element simulations. Across all tests, first-cycle softening and strain-dependent stress softening emphasized the importance of initial activation and the selection of materials with minimal plastic deformation. Airtightness and functional reliability were validated through the fabrication of diverse monolithically printed devices, including a soft robotic hand, an underwater robotic fish, and a wearable pressure cuff.
This work establishes Fused Granulate Fabrication (FGF) as a robust and versatile manufacturing strategy for both rapid prototyping and scalable production of large, complex soft devices. Soft materials within the Shore 00 hardness range, previously fabricated exclusively through soft lithography, can now be digitally manufactured using FGF, providing a modern and scalable alternative. FGF enables the reliable extrusion of silicone-soft thermoplastics with Shore hardness values as low as 6A and the fabrication of airtight structures at significantly higher throughput than conventional FFF systems, overcoming key limitations through coordinated optimization of materials, hardware, and process parameters. We demonstrate that rheological properties can be used as predictive indicators to identify pellets that minimize oozing, removing the need to modify printer hardware.

8 Experimental Section

Pellet printer setup: We used an Ender 3 Pro Plus FFF printer as the base platform. The standard filament extruder was replaced with a Direct3D pellet extruder. To improve feeding reliability, the Direct3D pellet hopper was redesigned with steeper wall angles to enhance gravitational flow, and its internal surfaces were coated with PTFE to reduce wall friction and prevent pellet bridging. A Raspberry

Pi 4 running Klipper firmware was integrated for direct process control, and slicing was performed using Cura (v5.8.1).

Material preparation: All compliant raw materials used in this study were commercially sourced (**Supporting Information, Table S1**). The TPS pellets selected for mechanical characterization and printing were obtained from Kraiburg TPE GmbH in Germany. To prevent moisture-related defects such as cavity formation due to water evaporation at the print nozzle, all filaments and pellets were pre-dried in a filament dryer (Sunlu S4) at 60°C for 6 hours and subsequently stored in a dry cabinet (Manncorp Ultra-Dry 790V) maintained below 5% relative humidity until use.

Extrusion test: For the extrusion flow rate test, the nozzle was preheated to the target temperature, after which the extrusion screw was rotated at a fixed speed for a set duration sufficient to collect a measurable amount of extruded material. Using the measured mass m, extrusion time t, and material density ρ, the volumetric flow rate was calculated as $Q = m/\rho t$. For the oozing test, the extrusion screw was rotated for 60 s, after which the nozzle was manually wiped immediately upon stopping. The subsequent oozing process was recorded on video, and the length of the oozed filament was later measured as a function of time.

Rheology experiment: Rheological properties were measured using a TA Instruments HR20 rheometer equipped with an environmental test chamber and a 25 mm parallel-plate geometry. For each material, a strain sweep was first performed to determine the linear viscoelastic (LVE) region. A strain amplitude of 1%, well within the LVE regime for all tested materials, was then used for oscillatory frequency sweeps. Frequency sweeps were conducted from 500 rad/s down to 0.05 rad/s, although in some cases measurements were terminated early due to material oozing from the plates. Prior to testing, all samples were dehydrated at 60°C for 6 hours, and before each measurement, samples were preheated to the target temperature for 180 s to ensure thermal equilibrium.

Tensile test experiment: All test bars were fabricated according to the ASTM D412 Type C standard with a thickness of 3 mm. TPE test bars were printed using either FFF or FGF, while silicone test bars were cast in molds fabricated via FFF. Tensile tests were conducted using a universal testing machine (Instron 68TM-50) equipped with a 500 N load cell. Following the standard, a strain rate of 500 mm/min was applied during testing. For each specimen, the initial clamp distance, width, and thickness were recorded to calculate strain and cross-sectional area. A prestress of 0.5 N was applied for most samples, while softer materials with Shore hardness below 10 A were tested using a reduced prestress of 0.1 N.

For cycling tests, the Instron 68TM-50 was programmed to pull the test bars between 0% strain and a specified maximum strain (varied depending on test conditions) for five consecutive cycles, followed by a final pull to a predefined maximum extension. All cyclic tests were performed at a strain rate of 500 mm/min, consistent with the uniaxial tensile tests.

PneuNet test setup: Each PneuNet was fabricated using the same print parameters as those employed for the mechanical test bars to ensure experimental consistency. The actuators were mounted on a fixed test frame against a black background, and images were captured at discrete pressure intervals. Bending angles were quantified from these images through post-processing. For cyclic testing, the same image-based analysis was applied to selected cycles. Actuation was controlled by an Arduino Mega, which applied 35 kPa at 5-second intervals to achieve near-complete bending in each cycle.

Simulation setup: The bending behavior of the pneumatic actuator was analyzed using COMSOL Multiphysics 6.2. A 3D stationary study was performed with a mesh defined in normal mode and element sizes ranging from 1 to 3 mm. A fixed boundary condition was applied to the surface containing the inlet connection. To capture mechanical interactions under high pressure, contact pairs were defined between adjacent chambers using a penalty factor of 1. Gravity was included in the vertical direction to replicate experimental conditions. Internal pressurization was simulated by applying a boundary load to the inner walls of the actuator. The bending angle was quantified by extracting the normal vector components (n_x and n_y) from the distal surface of the actuator.

Material behavior was modeled using a third-order Ogden hyperelastic model (**Supporting Information, Section 6**). The model parameters for each material were fitted to true stress–strain data obtained from uniaxial tensile tests.

Demonstration setup: The robotic hand comprises 15 individually controlled pneumatic actuators. Each actuator was connected to a 12V solenoid valve (0520F), driven by a MOSFET driver module (YYNMOS-4) and controlled using an Arduino Mega 2560. The actuators in the index, middle, ring, and pinky fingers were operated at a uniform pressure of 90 kPa, while the thumb actuators were driven at a lower pressure of 15 kPa.

The robotic fish contains two internal pneumatic chambers. To maximize bending, pressure was applied to one chamber while a vacuum was simultaneously applied to the other. This differential actuation utilized four solenoid valves, two supplying positive pressure and two supplying vacuum, to achieve bending through controlled asymmetric pressurization. Both positive and negative pressures were generated by a 12V pump (SC3802PM-A). For underwater testing, the head of the robotic fish was removed to simplify fixture mounting and ensure stable positioning during actuation (**Movie S5**).

In the pressure sleeve, all chambers were connected to a single pneumatic line to enable single-input control. A pressure regulator (AFR2000) was used to limit the maximum supply pressure, and airflow was modulated by using tubing with a narrow inner diameter of 1.5 mm. Internal pressure was measured using a piezoresistive pressure sensor (XGZP6847A500KPG) connected to an analog-to-digital converter (ADS1115).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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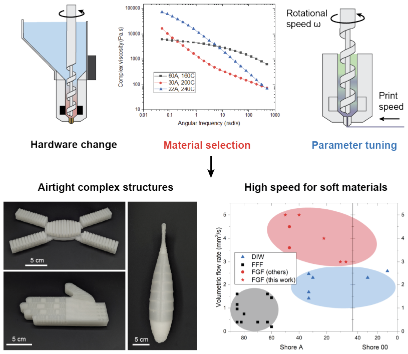

Fused Granulate Fabrication (FGF) is established here as a reliable and reproducible method for fabricating soft, airtight devices. Through coordinated optimization of hardware, material selection, and process parameters, this approach enables high-speed printing of thermoplastic elastomers with silicone-like softness and modulus. Systematic studies of extrusion stability, oozing behavior, and mechanical performance define a quantitative workflow that supports scalable, high-throughput manufacturing of soft devices.