

BIOGEM: A Fully Biodegradable Gelatin-Based McKibben Actuator with Embedded Sensing

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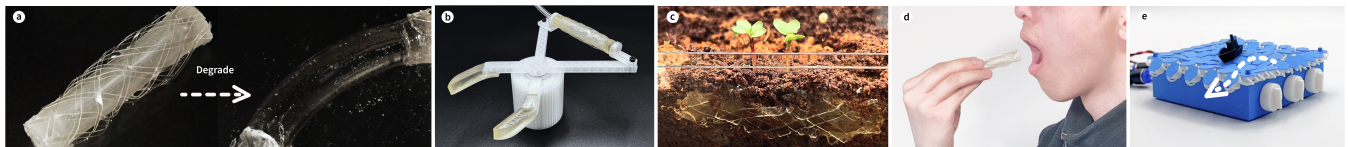


Figure 1: (a) A BIOGEM actuator undergoes enzymatic biodegradation. (b) A biodegradable scissor-like gripper actuated by BIOGEM. (c) A green sprout emerges from a decomposed BIOGEM soil robot. (d) Demonstration of BIOGEM actuator's edible nature. (e) An interactive desktop wave simulator made of BIOGEM.

Abstract

We present BIOGEM, a fully biodegradable McKibben actuator with integrated sensing, made from gelatin-based composites. By tailoring the material compositions, we customize the mechanical and electrical properties of the biodegradable composites, creating an integrated biodegradable system that combines both actuation and sensing functionalities. BIOGEM integrates a McKibben actuating structure by using stiff gelatin as outer braiding and the stretchable gelatin as air chambers. It also integrates resistive strain sensing through ionic gelatin, allowing the actuator to monitor its own deformation without relying on conventional electronics. We characterize the actuator's performance across key parameters including braid angle, wall thickness, and material stiffness, demonstrating reliable contraction and repeatable force output at low pressures. Biodegradation is validated through both enzyme-assisted and backyard soil studies, confirming the material's sustainable end-of-life behavior under realistic conditions. We illustrate the potential of this platform through interactive, edible, and

environmentally-degradable prototypes across human-computer interaction and soft robotics scenarios.

CCS Concepts

• **Human-centered computing** → **Interaction devices**.

Keywords

Soft actuator, stretchable sensor, sustainability, fabrication

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1 INTRODUCTION

Soft robotics has been extensively explored across diverse fields such as agriculture, wearable technology, manufacturing, and Human-Computer Interaction (HCI), due to its flexibility, adaptability, and safe interaction with complex environments and human users. Pneumatic actuators, in particular, have gained popularity for their strong actuation performance, high force-to-weight ratio, and versatile form factors suited to human-centered or delicate tasks [12, 27, 38]. A widely adopted approach within this domain is the use of McKibben actuators, which generate contractile motion through

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internal pressurization and offer a compact structure with compliant force output. Their mechanical characteristics make them well suited for integration into textiles, wearables, and other human-centered systems [1].

Conventional soft robotic systems predominantly utilize synthetic, petroleum-based materials such as silicone and thermoplastic polyurethane (TPU) [22, 40]. These materials resist natural degradation, posing sustainability challenges for prototyping workflows and deployed systems and contributing significantly to ecological degradation. Global production of silicone continues to increase steadily by approximately 5–6% annually, with an estimated output of 2.9–3.0 million metric tons in 2024. Most silicone waste is currently incinerated or landfilled, resulting in substantial resource loss and CO₂ emissions. Although chemical recycling of silicone has emerged as an alternative, it remains limited, with only 35,000 to 45,000 metric tons (barely over 1% of total silicone production) projected to be recycled chemically worldwide in 2024 [58].

With increasing emphasis on green technology, recent research has explored biodegradable and compostable materials for applications in soft robotics and shape-changing interfaces. Materials such as natural polymers, gelatin-based organogels, and biodegradable elastomers have been used to create soft robotic systems with environmentally friendly properties. These materials enable functions like shape change, actuation, and passive deformation through mechanisms such as swelling, shrinking, or pneumatic expansion [23, 43, 57]. While these approaches offer promising advances, many still depend on non-biodegradable components for sealing, structural reinforcement, or sensing. A fully biodegradable soft robotic system remains challenging to realize due to the need to integrate diverse components, including the structural, shape-changing, and sensing components, each requiring distinct mechanical and electrical properties. The limited availability of biodegradable materials makes it hard to meet the specific needs for each component.

To this end, we present BIOGEM, a fully biodegradable McKibben-style pneumatic actuator with embedded sensing. All components in BIOGEM, including the air chamber, end caps, McKibben braiding, interconnecting tubes, and resistive strain sensors, are made of biodegradable gelatin-based composites. By modifying the base gelatin composite with additives such as sugar, glycerol, and NaCl, we achieve the diverse material properties required for different components and customize the performance of BIOGEM. Our actuator reliably achieves measurable mechanical contraction, repeatable force output, and continuous strain sensing, all without relying on synthetic polymers or adhesives. Through systematic mechanical, electrical, and biodegradation tests, we validate the actuator’s performance, durability, and sustainable end-of-life behavior. Lastly, we showcase the actuator’s applicability across multiple domains, including soil-degradable agricultural robots, wearable artificial muscles, desktop interactive devices, and edible interactive cakes. Our contribution marks a significant step toward fully sustainable and broadly accessible actuation systems in soft robotics and HCI.

Specifically, this paper contributes the following:

- A fully biodegradable gelatin-based McKibben actuator with integrated sensing.

- Mechanical characterization of gelatin-based composites, highlighting their customizable mechanical and electrical properties.
- Performance evaluation of BIOGEM, demonstrating reliable mechanical contraction, repeatable force output, and integrated real-time strain sensing.
- Demonstrations of BIOGEM in diverse using scenarios, including biodegradable soil robots, artificial muscles, desktop interactive devices, and edible interactive cakes.

2 RELATED WORK

Understanding prior work in soft actuation, sustainable materials, and embedded sensing is essential for contextualizing our biodegradable McKibben actuator. In this section, we review related work in pneumatic actuators, sustainable materials in HCI, and integrated sensing in soft systems.

2.1 Pneumatic Actuators

Pneumatic actuators are widely employed in soft robotics due to their high compliance, simple structure, and effective force generation [1]. They typically comprise air chambers designed with anisotropic mechanical properties in materials [34, 66] and configurations [38, 55, 56, 59] that enable extension [1, 47, 56], contraction [17, 47], bending [10, 22], twisting [55, 63], and omnidirectional [22, 66] movements. A prominent example is the McKibben actuator, which encloses an inflatable inner bladder within a braided sleeve to convert radial expansion into axial contraction, thereby producing strong and controllable actuation forces [1, 3].

McKibben actuators have been widely adopted in applications requiring soft, bio-mimetic motion and high force output. In the field of rehabilitation robotics, they are often used as artificial muscles that replicate human contraction behavior, enabling joint assistance and motor function recovery. Their pneumatic compliance, low weight, and ability to generate muscle-like motion make them ideal for wearable systems such as active suits and exoskeletons for upper and lower limb rehabilitation [9].

In addition to medical applications, McKibben actuators are used in industrial and mobile robotic systems for tasks that require strong yet compliant actuation. Their structure, which consists of an inflatable inner tube constrained by a braided outer sleeve, allows them to generate substantial contractile forces without relying on complex gear systems or rigid mechanical components. This makes them suitable for robotic arms, grippers, and manipulators where weight, flexibility, and safety are critical. Their pneumatic actuation also enables remote pressure control through lightweight tubing, which supports modular and portable designs [29].

Building on such progress, our approach revisits the classic McKibben configuration and maintains strong contractile motion with integrated sensing, while also laying the groundwork for more eco-friendly material choices.

2.2 Sustainable Materials in HCI

Conventional pneumatic actuators in soft robotics are commonly fabricated using elastomers such as silicone through casting or molding processes [40], or via additive manufacturing techniques like 3D printing [7]. These fabrication methods offer high repeatability and robust mechanical performance [49, 64], making them

Work	Actuation Mechanism	Sustainability	Sensing Integration	Fabrication Accessibility
Peano-HASEL [46]	Electrohydraulic actuation	~ Biodegradable under industrial composting	× None	× CNC & oil injection
PITAS [12]	Thermally-driven sheet actuator	× Not biodegradable	✓ Capacitive & resistive sensing	✓ Laser cutting & casting
OmniFiber [1]	McKibben actuator	× Not biodegradable	✓ Strain sensing	× Knitting & carbon coating
SoftBioMorph [42]	Pneumatic & hygroscopic actuation	✓ Plant-derived elastomer	× None	✓ Simple casting
BIOGEM (ours)	McKibben actuator	✓ Gelatin-based composites	✓ Strain sensing	✓ Casting & laser cutting

Table 1: Comparison of related work. BIOGEM offers unique advantages in sensing integration and low-barrier fabrication.

widely adopted in the field. However, they typically rely on non-biodegradable materials that persist in the environment after disposal [22], presenting a significant challenge for sustainability.

In response to these concerns, researchers in HCI and related fields have made responses from varied angles, including life cycle analysis [65], computational design optimization [11, 44], digital fabrication [18, 42], and material selection [2, 38, 43]. Terms like “sustainable,” “biodegradable,” and “eco-friendly” each underscore different aspects of a product’s environmental impact, from resource usage to decomposition at end-of-life [23, 43].

Recent work has introduced biodegradable and biocompatible materials into interactive systems. For example, researchers have used plant-based biopolymers and gels to create components that decompose naturally after use [25, 43]. In the actuator domain, efforts like biodegradable electro-hydraulic systems constructed from natural rubber and gel-based insulators have shown the potential to merge sustainability with functionality [46]. In the realm of shape-changing interfaces, SoftBioMorph employs sodium alginate and other biopolymers, combining pneumatic actuation with design strategies that emphasize visual and tactile transformation [42].

Building on top of these pioneering works, our work focuses on introducing a fully biodegradable actuator system capable of delivering substantial pneumatic force, making it suitable for soft robotics applications. Specifically, we explore gelatin-based composites with tunable mechanical properties to address the intrinsic material demands of McKibben actuators. While prior research has investigated gelatin-based actuators [28, 41, 46], none have fully satisfied the diverse material requirements necessary for a McKibben configuration, which typically demands a range of elastic, flexible, and rigid components. BIOGEM overcomes these limitations by employing a gelatin-based composite enhanced with sugar, glycerol, and NaCl, which enables integrated actuation and strain sensing within a single biodegradable material system. Additionally, compared to previous approaches that rely on specialized direct-ink-writing (DIW) bioprinters or customized printing setups [41], our fabrication method offers a simpler and more accessible alternative achievable within typical maker environments. BIOGEM retains the expressive qualities of biodegradable interfaces while enabling active movement and sensing, effectively bridging a critical gap between sustainable design and functional soft robotics in HCI.

2.3 Integrated Sensing in Soft Robotics

Embedding sensing into soft robotic systems allows for responsive feedback and interactive behavior. Prior strategies have successfully demonstrated embedded sensing by integrating conductive yarns or liquid-metal channels into elastomeric actuators, enabling pressure or strain detection through stretchable structures [30, 51]. Luo

et al. extended these ideas by embedding resistive and capacitive sensors into machine-knitted actuators, achieving robust sensing without external electronics [38]. PITAS builds on similar goals by supporting multi-modal sensing through conductive silicone layers in a thin, flexible sheet format [12]. These systems demonstrate the feasibility of integrated sensing in soft platforms and highlight the potential for multi-functional, compact designs.

Building upon these efforts, our actuator introduces a resistive strain sensor made from NaCl-infused gelatin. The sensor is integrated during fabrication with the actuator, preserving full biodegradability while eliminating the need for adhesives or additional electronics. To our knowledge, this is the first instance of a fully biodegradable McKibben actuator with integrated strain sensing, tailored for sustainable HCI and soft robotics applications.

3 SYSTEM OVERVIEW

BIOGEM consists of McKibben actuators and strain sensors. Both the actuation and sensing performance are achieved through selected gelatin-based composites. We drive the actuators and serialize sensing data via a couple control and read out circuit. This section provides a detailed discussion of each gelatin components and system setup for actuation and sensing, shown by Figure 2.

3.1 Gelatin-Based Composites

The composite used in our actuator is composed of gelatin, sugar, glycerol, water, and sodium chloride (NaCl). Each ingredient is selected to customize the composite’s mechanical and electrical behaviors.

Gelatin serves as the base material, forming a rigid biopolymer network when cooled and dried [6]. While gelatin alone is brittle, it provides the necessary structural framework. Its mechanical properties can be adjusted with additives, allowing it to function as either a stiff component or, when plasticized, a stretchable component [8, 16, 19]. Sugar modifies the gelatin matrix by interfering with the hydrogen bonding network. While not a classic plasticizer, sugar can soften the composite by increasing free volume and retaining moisture [8]. This helps reduce brittleness and enhances flexibility, especially at moderate concentrations. Glycerol is a traditional plasticizer. It inserts between gelatin chains and weakens intermolecular interactions, significantly increasing stretchability and elasticity while preventing cracking during repeated use [21, 33]. NaCl is added for electrical conductivity. Dissolved sodium and chloride ions form ionic pathways within the gelatin, enabling strain-based resistance sensing as the material deforms [20, 21]. During material preparation, all ingredients are dissolved and blended in the water. In the final composites, residual water

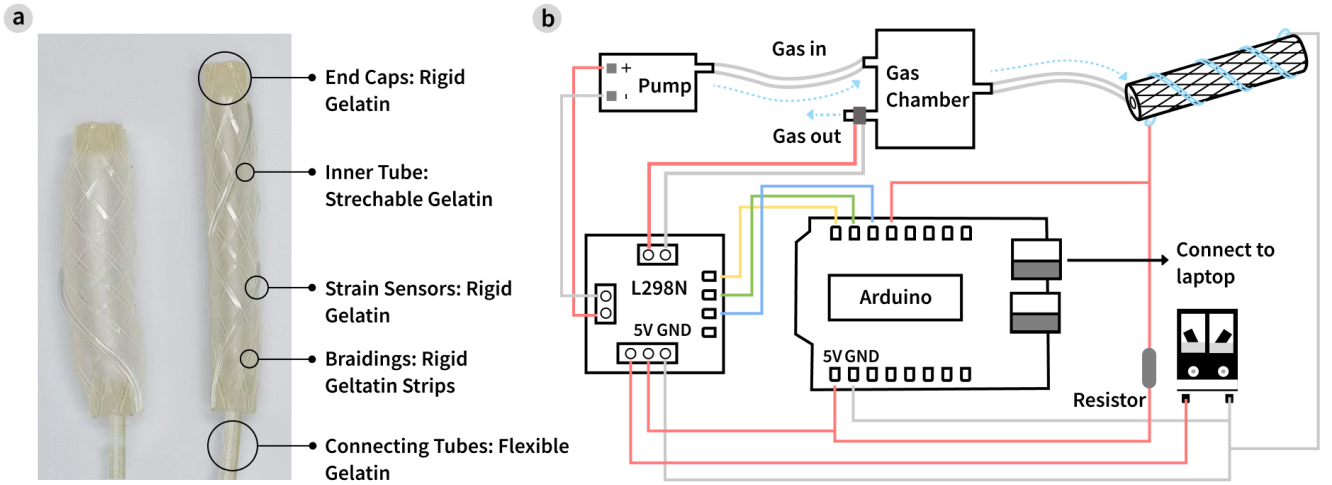


Figure 2: System overview of the gelatin-based McKibben actuator with embedded sensing. (a) Gelatin actuator in relaxed and pressurized states, with annotations indicating the specific gelatin type used for each component. (b) System setup for actuation and sensing using an Arduino-based circuit.

helps retain softness and flexibility by keeping the gelatin network hydrated [37].

Together, these components form a biodegradable and tunable composite system. By varying the composition, we can achieve different levels of rigidity, stretchability, and conductivity to meet the specific demands of each actuator component.

3.2 Biodegradable McKibben Actuator

The actuator design presented in this work follows the classical McKibben actuator configuration, composed of four primary components: an inflatable inner tube, a braided sleeve, end caps, and connecting tubes, shown by Figure 2a. The working principle of our actuator is based on converting radial expansion into axial contraction through a braided structure. When pressurized air is introduced into the inflatable inner tube, the internal pressure causes the tube to expand radially. However, the braided sleeve surrounding the inner tube constrains this expansion due to its rigid structure and high Young's modulus, forcing the tube to shorten axially as the braid angle changes.

Inner Tube. The inner tube is fabricated from stretchable gelatin, selected for its high elasticity and ability to undergo large deformations without permanent damage. This stretchability supports repeated expansion and contraction cycles, which are essential for reliable actuator performance. Its compliant nature enables the actuator to achieve substantial axial contraction under pneumatic pressure.

Braided Sleeve. The braided sleeve is made from rigid gelatin sheets laser-cut into thin strips and woven around the inner tube. The rigidity and braid angle of these gelatin strips are crucial in limiting radial expansion of the inner tube, thereby effectively converting radial pressure into axial contraction. The sleeve's precise braid structure directly influences the actuator's contraction ratio and force output [5, 15].

End Caps. The rigid gelatin end caps provide structural reinforcement and reliable sealing of the inner tube. Their higher stiffness prevents air leakage, preserving actuator performance and efficiency. Additionally, the biodegradability of these end caps aligns with the actuator's overall sustainability goals.

Connecting Tubes. The connecting tubes are fabricated from a less stretchable gelatin composite, providing an airtight and structurally stable pathway for controlled air delivery. Their rigidity helps preserve the actuator's overall geometry during inflation and ensures consistent actuation performance by minimizing undesired deformation.

All components, including the inner tube, braided sleeve, end caps, and connecting tubes, are fabricated from gelatin-based composites. The mechanical properties of these components are precisely customized through variations in gelatin composition, such as sugar, glycerol, and NaCl additives, achieving distinct functional properties such as elasticity, stiffness, and conductivity. This careful tuning allows the actuator to maintain full biodegradability while meeting diverse mechanical and functional requirements for soft robotic applications.

3.3 Biodegradable Strain Sensor

The actuator incorporates a biodegradable strain sensor made from conductive gelatin—a composite of gelatin infused with NaCl to introduce electrical conductivity. These sensors are cast into thin strands and wrapped around the inner tube, following the braided sleeve pattern to ensure seamless integration within the actuator structure, as shown in Figure 2a. The BIOGEM actuator is powered by a standard 6 to 9-volt pneumatic pump and consumes comparable power to other pneumatic biodegradable actuators. The system setup for actuation and sensing using an Arduino-based circuit is shown in Figure 2b.

As the actuator inflates, the conductive gelatin strands undergo tensile strain, which increases the distance between the integrated

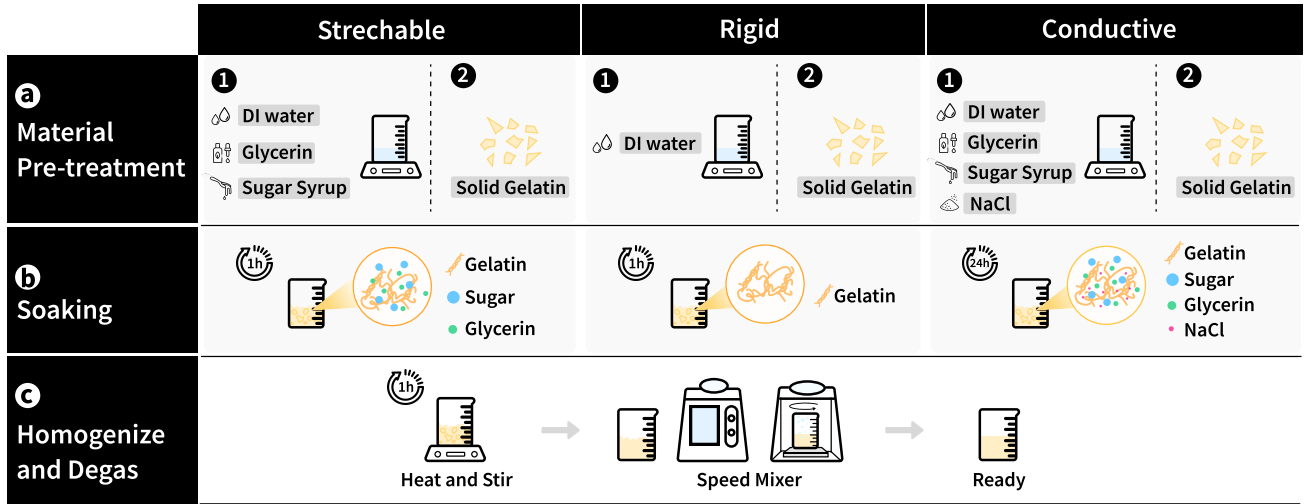


Figure 3: Material preparation process for gelatin-based composites. (a) Pre-treatment of ingredients for each composite type. (b) Soaking of solid gelatin into prepared mixtures for hydration. (c) Homogenizing and degassing using heat and speed mixing.

ionic particles and leads to a measurable increase in resistance. By continuously monitoring this resistance change, we can infer the degree of inflation and deformation in real time. This built-in sensing capability enables the actuator to provide continuous feedback on its state, supporting interactive control in soft robotic applications.

Unlike conventional sensing systems that rely on separate, non-biodegradable components, our design fully integrates actuation and sensing using the same biodegradable material platform. This approach not only simplifies fabrication but also enhances sustainability by enabling a fully biodegradable system with built-in sensing, allowing the actuator to monitor its state and respond dynamically during operation.

4 FABRICATION

BIOGEM is fabricated through a structured process that includes material formulation, component fabrication, and assembly. All components are made from biodegradable gelatin-based composites with distinct mechanical or electrical properties. The process integrates casting, cutting, braiding, and bonding techniques to form the actuator structure, followed by the addition of embedded sensing elements.

4.1 Material Preparation

BIOGEM is made of three main types of gelatin-based composites: stretchable gelatin, rigid gelatin, and conductive gelatin. All composites undergo a consistent preparation method with three key steps: material pre-treatment, soaking, and homogenization followed by degassing. The materials employed include sheet/leaf gelatin, purified glycerol (HiMedia GRM081-1L), liquid glucose syrup, deionized (DI) water, and NaCl (for conductive gelatin). The complete preparation workflow for the three composite types is illustrated in Figure 3. Different material compositions, as listed in Table 2, are heated and stirred on a hotplate before gelatin is added to each solution. The mixtures are then soaked to ensure thorough

hydration and dispersion—approximately 1 hour for stretchable and rigid gelatin composites, and 24 hours at room temperature for conductive gelatin. After soaking, each composite is reheated to 80 °C with continuous stirring to fully dissolve the gelatin. Finally, all gelatin solutions are homogenized and degassed using a speed mixer to remove air bubbles and ensure uniform composite quality.

4.2 Fabrication of McKibben Actuators

The gelatin McKibben actuator consists of the inner tube, end caps, connecting tube, strain sensor, which are molded, and lasercutted braided sleeves. The overall fabrication process is illustrated in Figure 4.

We fabricate the actuators primarily using casting with 3D-printed PLA molds printed by Bambu Lab P1S. To obtain the inner tube, the liquid stretchable gelatin composite is poured into the mold. After curing for approximately 30 minutes, the mold is disassembled, giving us a hollow cylindrical tube. The rigid gelatin end caps are similarly fabricated by casting. Molds can be customized to meet specific application requirements. For air supply connection, thinner and longer tubes are cast by modifying the dimensions of the inner tube mold.

Subsequently, we employ a custom-designed braiding tool to wrap laser-cut rigid gelatin strips around the soft inner tube, shown by Figure 4a. This tool allows control over braid patterns and angles to achieve specific mechanical behaviors. The braiding tool consists of a central cylindrical core and two adjustable fixtures, each with evenly spaced slots that guide the strips into a helical pattern. Then, braided sleeves are attached onto the soft tube using a soldering iron at 80°C to lightly melt contact points.

To attach the end caps to inner tube, shown by Figure 4b, the inner wall of the inner tube is slightly melted using a soldering iron, and the end caps are dipped into hot water (80°C) and pressed into the inner tube. This method improves bonding and ensures air tightness. The actuator assembly is completed by connecting gelatin-based tubes for air supply.

Composite Type	Gelatin (%)	Glycerol (%)	DI Water (%)	Sugar Syrup (%)	NaCl (%)
Stretchable	15	30	30	25	0
Rigid	33	0	67	0	0
Conductive	27	30	20	20	3

Table 2: Formulation of gelatin-based composites used in BIOGEM. Each formulation is prepared through a standardized process involving material pre-treatment, soaking, homogenization, and degassing, as demonstrated in Figure 3.

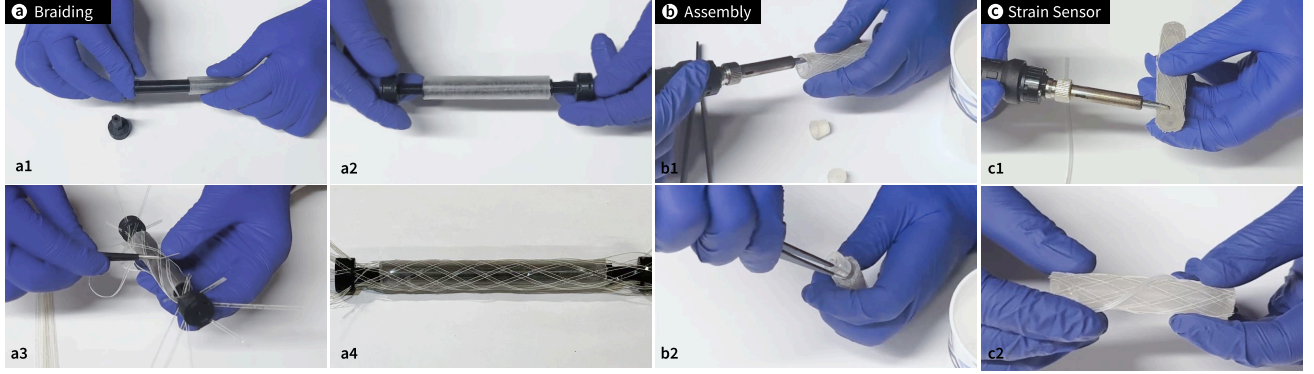


Figure 4: Fabrication process. (a) Braiding: (a1) load the inner tube onto the braiding tool, (a2) assemble the braiding tool, (a3) perform the braiding process, (a4) complete the over-braiding on the actuator. (b) Assembly: (b1) use a soldering iron to melt the inside of the inner tube, (b2) insert the end caps into both sides of the tube. (c) Strain sensor: (c1) use a soldering iron to melt the contact point between the inner tube and the strain sensor, (c2) attach the strain sensor onto the actuator's surface.

4.3 Fabrication of Strain Sensors

To obtain sensing capabilities, the strain sensor is fabricated using conductive gelatin. A thin rubber tube is used to draw liquid conductive gelatin. Once the tube is filled and the gelatin is cured, slit open the rubber tube, then we obtain a wire-shaped conductive gelatin, which functions as a strain sensor. The sensor can be wrapped around the actuator, with both ends attached using a soldering iron, as shown by Figure 4c. During actuation, the actuator expands radially, stretching the sensor and increasing its electrical resistance. This change in resistance can be used to detect the actuation state or other sensing applications.

5 CHARACTERIZATION AND RESULTS

To evaluate and optimize the performance of our biodegradable actuator system, we conduct a series of experiments covering material mechanics, actuator behavior, sensor responsiveness, and environmental degradability. These evaluations are guided by the actuator's intended use in HCI contexts, emphasizing reliability, responsiveness, and sustainability for interactive and shape-changing systems.

5.1 Mechanical Properties of Gelatin-Based Composites

We perform axial tension tests on different gelatin composites to examine how sugar and glycerol concentrations influence the elasticity, strength, and stability of gelatin-based composites. Our tests follow the ASTM D412-c standard using an Instron 5585H load

frame with a 50 N load cell and pneumatic grips. Samples are cast using custom FDM-printed molds. Two series of samples are prepared: one with varying sugar concentrations (0.0%, 10.4%, 18.9%, 25.9%, and 31.8% by weight) and another with varying glycerol concentrations (0.0%, 12.2%, 21.7%, 30.8%, and 37.9% by weight). The corresponding stress-strain curves and Young's modulus values are shown in Figure 5.

As the concentrations of sugar and glycerol increase, the elastic modulus of the gelatin-based composites decreases (Figure 5b and e). This trend indicates that both additives function as effective softening agents. As shown in Figure 5a and d, our characterization enables precise tuning of Young's modulus (0.071 MPa to 132.32 MPa). Additionally, sugar and glycerol concentrations have opposing effects on ultimate tensile strength (UTS): increasing sugar content from 0 to 31.8% raises the UTS from 0.312 to 0.910 MPa, whereas increasing glycerol content from 0 to 37.9% reduces the UTS from 4.694 to 0.894 MPa.

Our results show that gelatin composite can be customized for various mechanical properties in different BIOGEM components. Softer composites are ideal for the inner tube as less work is required for contraction. In contrast, stiffer formulations (lower sugar/glycerol) are better for load-bearing components such as the braided sleeve or end caps, where rigidity and structural support are necessary.

We also evaluate material stability by measuring the water losses of the composites after 24 hours in a fume hood. According to Figure 5c and f, the higher sugar and glycerol content results in significantly lower water evaporation[41]. These results suggest

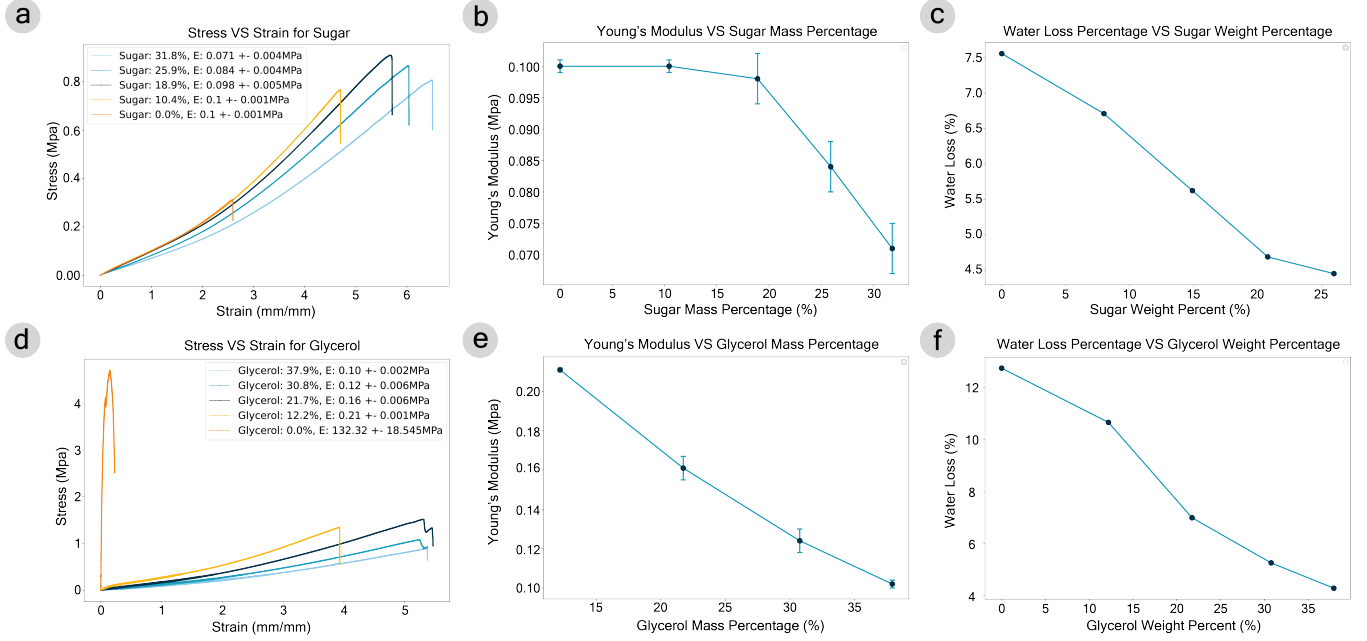


Figure 5: Experimental results of gelatin composites' mechanical properties. (a) Stress-strain curves for varying sugar weight percentages. (b) Young's modulus for varying sugar weight percentages. (c) Water loss percentage for varying sugar weight percentages. (d) Stress-strain curves for varying glycerol weight percentages. (e) Young's modulus for varying glycerol weight percentages. (f) Water loss percentage for varying glycerol weight percentages.

that sugar and glycerol help retain moisture, improve the stability of material mechanical properties in the long term [39].

5.2 Actuator Performance

We investigate how key design choices affect the performance of McKibben actuators, specifically focusing on two main metrics: contraction ratio and blocking force [5, 15]. These metrics are commonly used indicators of actuator effectiveness. Contraction ratio affects how far the actuator can move, while blocking force determines the actuator's ability to interact with physical objects or support loads. Our goal is to understand how changes in geometry and materials can be used to customize these performance characteristics.

Test Setup and Method. To measure the blocking force, we use an Instron 6844 load frame with a 50 N load cell, as shown in Figure 6a. Custom 3D-printed mounts ensure secure attachment without damaging the actuator. Both ends of the actuator are fixed to the load cell mounts, with one end also connected to the pressure source. The actuator remains constant length during the test (zero strain rate), and forces of contraction are recorded by the load cell. Contraction was measured manually using calipers at different pressure levels.

Braid Angle. In McKibben actuators, the braided sleeve pattern is the key constraining component that affects the actuator's performance. The braid angle defines the relationship between radial expansion and axial contraction, and plays an important role in actuator contraction when inflated [2, 4].

We fabricate actuators with six braid angles: 14.41°, 18.92°, 23.19°, 27.21°, 34.43°, and 40.59°, while keeping all other design parameters constant. The braid angle (θ) is calculated by the geometric relationship between the tube and the braiding fixtures [5, 15]. It is calculated as:

$$\theta = \tan^{-1} \left(\frac{\pi D \Delta s}{NL} \right) \quad (1)$$

where D is the outer diameter of the soft tube, Δs is the slot offset between the two fixtures, N is the number of slots per fixture, and L is the axial distance between the two fixtures.

Shown in Figure 6b, actuators with larger braid angles show higher contraction. The results reveal a clear trade-off between contraction range and output force. The 40.59° actuator achieves a contraction ratio of approximately 14.8% at 16 kPa. However, this comes at the cost of reduced blocking force. According to Figure 6e, the 27.21° actuator produces the highest force, reaching 8.0 N at 12 kPa. BIOGEM generally follows the behavior of classic McKibben actuators. Contraction increases with braid angle up to a peak, then decreases. However, our peak occurs at a higher angle (40.6°) than typical (25° to 30°). This shift is due to material differences: unlike conventional models that assume a radially stiff inner tube [15], our gelatin tube exhibits greater radial compliance at low pressures, allowing axial shortening even at higher braid angles.

These results suggest that higher braid angles are preferable for applications prioritizing large, expressive deformation, while moderate braid angles are better suited for force-intensive tasks. Additionally, fabrication time increases with larger braid angle due

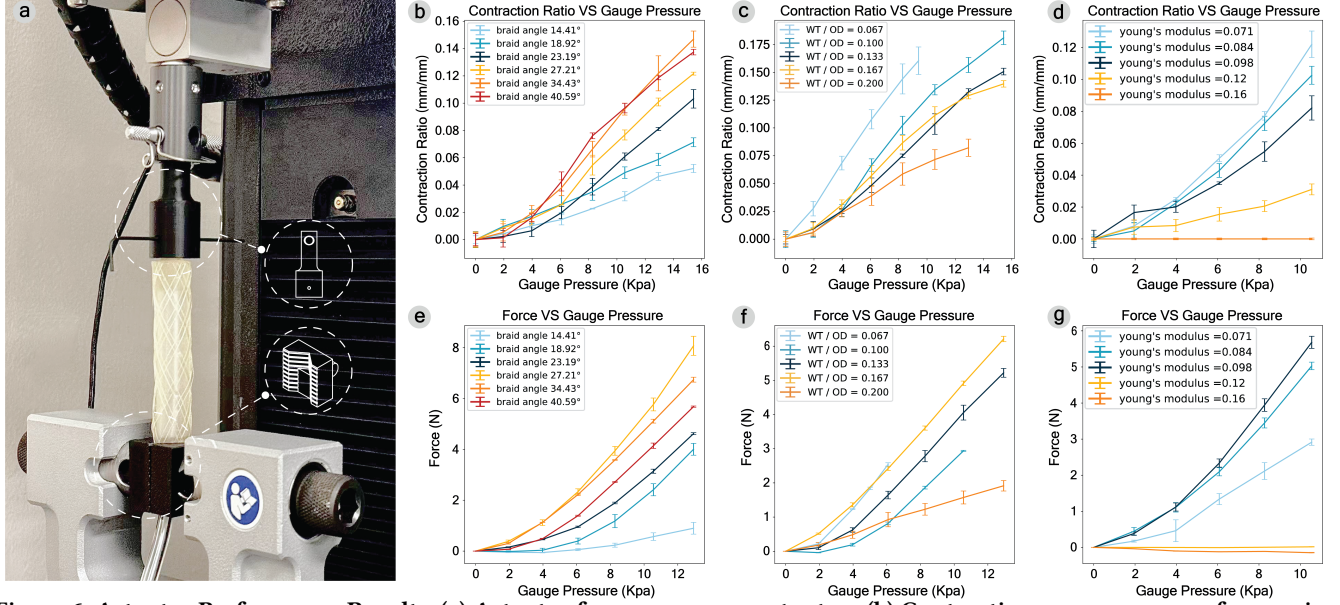


Figure 6: Actuator Performance Results. (a) Actuator force measurement setup. (b) Contraction versus pressure for varying braid angle. (c) Contraction versus pressure for varying wall thickness. (d) Contraction versus pressure for varying young's modulus. (e) Force versus pressure for varying braid angle. (f) Force versus pressure for varying wall thickness. (g) Force versus pressure for varying young's modulus.

to tighter braiding. Considering all factors, we identify 27.21° as the optimal balance between contraction, force, and manufacturability.

Wall Thickness to Radius Ratio. We then explore how the thickness of the actuator's inner wall contributes to performance. Unlike the braid angle, which affects the overall deformation pattern, wall thickness primarily defines the ease of material expansion under pressure [13, 36]. We fabricate actuators with a fixed outer diameter of 15 mm and vary wall thickness across five levels: 1 mm, 1.5 mm, 2 mm, 2.5 mm, and 3 mm. These correspond to thickness-to-diameter ratios of 0.0667, 0.100, 0.133, 0.167, and 0.200. All other design parameters remain constant. Shown by Figure 6c, thinner walls consistently produce higher contraction. The actuator with the thinnest wall (0.0667 ratio) achieves a peak contraction of approximately 16% at 9 kPa. This aligns with the intuition that lower wall stiffness facilitates radial expansion, which in turn drives greater axial shortening [13, 24, 36]. However, shown by Figure 6f, actuators' force does not follow a clear trend. While actuators with mid-range thicknesses, such as 0.133, appear to balance both contraction and force output, overall variability suggests that force is influenced by more than wall geometry alone—possibly including factors like material stiffness, pressure distribution, contraction dynamics, and interaction between braid and tube [27].

These results suggest that wall thickness should be selected based on the intended application. For tasks that require large, smooth deformation, thinner walls are ideal. For tasks involving physical interaction or load-bearing, wall thickness must be carefully balanced with other parameters to avoid compromising strength.

Young's Modulus of Materials. To better understand how material stiffness affects actuator performance, we examine the role of

the inner tube's Young's modulus in actuator performances. We fabricate actuators using gelatin-based composites with five different Young's modulus: 0.071 MPa, 0.084 MPa, 0.098 MPa, 0.12 MPa, and 0.16 MPa, while keeping all other design parameters constant. Shown by Figure 6d, the contraction data reveals a clear trend: as Young's modulus increases, contraction ratio decreases. When the modulus reaches above 0.12 MPa, contraction drops sharply. This aligns with the observation that a stiffer inner tube can hinder radial expansion, which is essential for achieving axial contraction [61].

Demonstrated by Figure 6g, the force measurements follow a two-part trend. For actuators with lower stiffness (0.071 to 0.098 MPa), increasing modulus leads to stronger force output. However, beyond 0.12 MPa, force by contraction cannot be recorded, further confirming that overly stiff materials limit both motion and usable force.

These results underscore the importance of material selection when designing soft actuators. A moderate modulus enhances force output, but there is a clear threshold beyond which the actuator becomes ineffective. For gelatin-based McKibben actuators, we identify 0.084–0.098 MPa as a practical range that balances motion and strength, enabling reliable and responsive actuation at low pressures.

Cyclic Test. To test actuator's reliability under repeated use, a force cyclic test is performed to assess the durability of our biodegradable actuator under cyclic actuation. We construct a simple pneumatic system for cyclic actuation. The actuator is inflated for 0.8 seconds and deflated for 1.0 second using a gas pump and solenoid valve controlled by an Arduino, as shown in Figure 2b. The actuator tested in this study is cycled over 550 times while continuously recording force output.

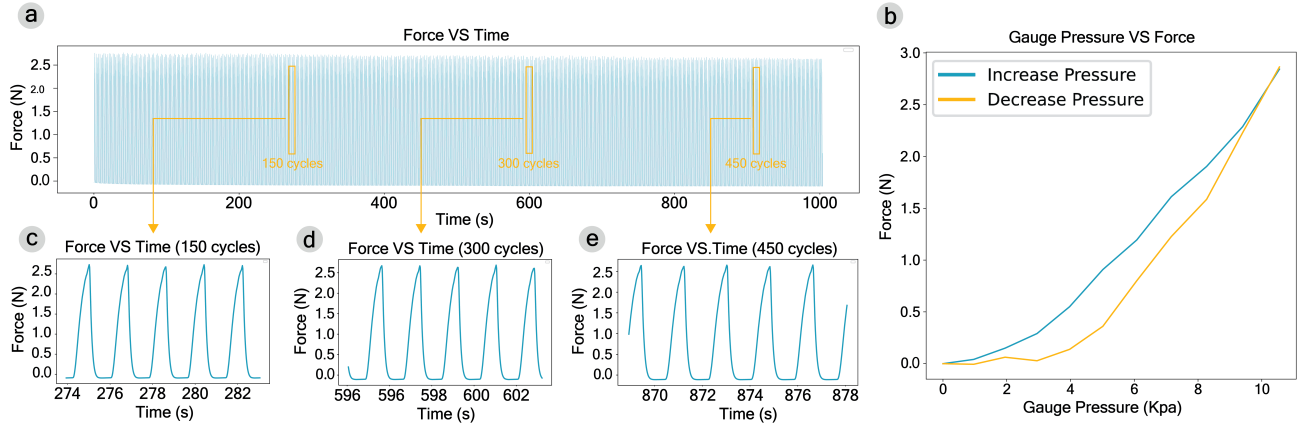


Figure 7: Actuator cyclic force testing. (a) Force-time response over 550 actuation cycles. (b) Force hysteresis during a single actuation cycle. (c)–(e) Force-time responses at approximately 150, 300, and 450 cycles, respectively.

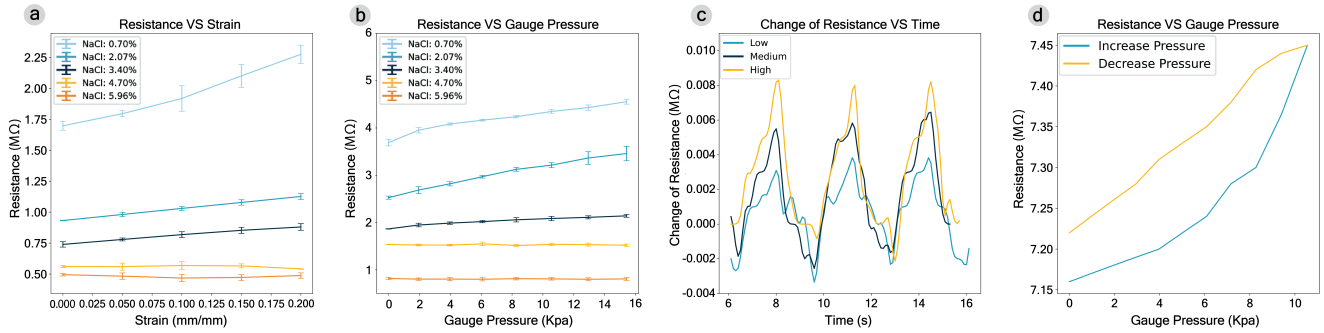


Figure 8: Gelatin strain sensor characterization. (a) Sensor resistance versus normal strain for different NaCl weight percentages. (b) Sensor resistance versus actuator internal pressure for different NaCl weight percentages. (c) Cyclic sensor performance at varying pressure levels. (d) Sensor resistance hysteresis during a pressure increase-decrease cycle.

As shown in Figure 7a, the actuator maintains stable peak forces without obvious force degradation during the test. Force traces sampled around cycles 150, 300, and 450 show highly consistent profiles, indicating excellent repeatability. This result confirms that the gelatin-based McKibben actuator retains reliable actuation behavior across prolonged use, an essential property for soft robotic systems operating in real-time or continuous interaction scenarios.

We also analyze actuator force hysteresis during one actuation cycle. Shown by Figure 7b, the result reveals a characteristic hysteresis loop, highlighting energy loss due to the viscoelasticity of the gelatin composite [26]. This loop shows that the actuator responds differently during pressurization and depressurization, which could impact timing or control precision in applications requiring tight feedback.

5.3 Strain Sensor Performance

In addition to actuation, real-time sensing is a critical component of responsive soft systems. In this section, we investigate how sensor behavior is affected by NaCl concentration and repeated use. Our goal is to identify formulations that offer high sensitivity

and reliability, enabling accurate and continuous feedback during operation.

NaCl Concentration. NaCl creates ionic pathways within the composite, enabling resistance-based deformation sensing. We fabricate five sets of gelatin-based sensors, each with a different NaCl weight percentage: 0.70%, 2.07%, 3.40%, 4.70%, and 5.96%. For each, we measure how resistance changes under tensile strain and under pressure when the sensor is wrapped around an inflating actuator.

The strain-resistance results, shown in Figure 8a, reveal a clear trend. Higher NaCl concentration leads to lower initial resistance as more ionic paths are created. For lower NaCl concentration (0.70% to 3.40%), we observe a desirable, near-linear increase in resistance with an increase of strain. However, at higher concentrations (4.70% and 5.96%), the resistance values exhibit minimal change during stretching. This saturation effect likely results from an excess of free ions, which overwhelms the signal response and reduces sensitivity [14, 62]. The same phenomenon appears in the pressure-resistance tests, shown in Figure 8b. When sensors are wrapped around pressurized actuators, resistance increases with actuator's expansion only at low NaCl concentrations.

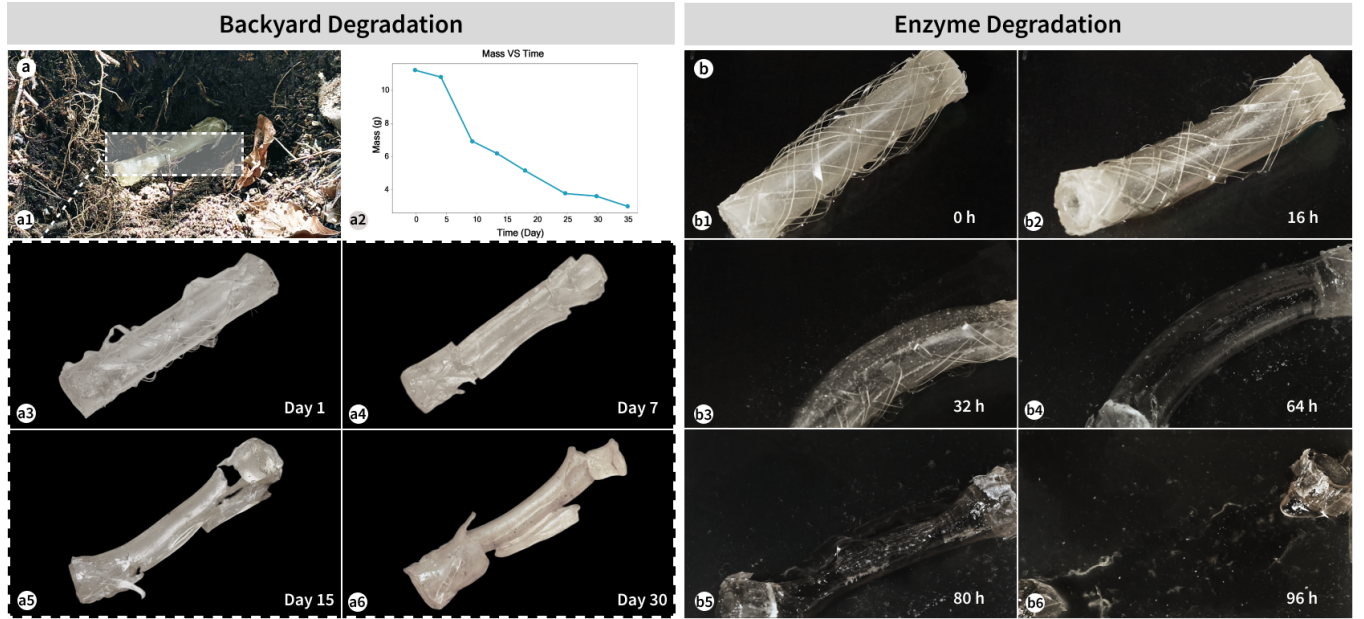


Figure 9: Biodegradation of gelatin-based actuator under natural and enzymatic conditions. (a) Backyard soil degradation: (a1) actuator placed in soil, (a2) mass loss of actuator over 35 days, (a3–a6) progressive degradation at Day 1, 7, 15, and 30. (b) Enzymatic degradation: (b1–b6) actuator degradation process in enzyme solution over 96 hours, showing progressive breakdown at 0 h, 16 h, 32 h, 64 h, 80 h, and 96 h.

Both results demonstrate that NaCl concentration plays a critical role in determining electromechanical properties of our sensor. For applications requiring both high conductivity and meaningful resistance change, a concentration between 2.07% and 3.40% offers the best balance. This range provides low baseline resistance with a stable, linear, and responsive signal across both strain and pressure stimuli.

Cyclic Test. We evaluate the gelatin-based strain sensor’s performance under repeated actuation cycles to assess its consistency in long-term use. The sensor is wrapped around the actuator and tested using Arduino circuit shown in Figure 2b. We set low, medium, and high pressure levels for actuation. The results, shown in Figure 8c, display distinct resistance patterns corresponding to each pressure level. Additionally, we conducted a 100-cycle test on the strain sensor, noting a 1.5% increase in resistance at the end. These tests confirm the sensor’s ability to deliver reliable, repeatable feedback across multiple cycles for practical applications.

We also perform a single-cycle hysteresis test. The resistance during depressurization does not follow the same path as during pressurization, and does not fully return to the initial value. This hysteresis is attributed to the viscoelastic and ionic nature of the gelatin composite [26, 48, 60].

5.4 Biodegradation

To evaluate the environmental degradability of our gelatin-based actuator, we conduct two types of biodegradation tests: a backyard soil burial test to simulate real-world disposal conditions and an enzyme-based degradation test using collagenase to mimic accelerated breakdown under controlled laboratory conditions. Figure 9

provides a visual comparison of these two degradation pathways, including placement setup, mass loss trends, and progressive breakdown of the actuator.

Backyard Degradation. In the backyard degradation test, actuators are buried 20cm below moist soil in an outdoor environment. At regular intervals, samples are retrieved, rinsed with deionized water, and dried in a fume hood for 24 hours to remove excess moisture. The dried samples are then weighed to measure material loss over time, a process repeated across multiple time points to track progressive degradation.

Shown by Figure 9a, the gelatin-based components exhibit visible degradation, with progressive weight loss over the testing period. Environmental factors such as temperature, humidity, and microbial activity influence the degradation rate, contributing to variations in decomposition speed. The backyard test demonstrates that the gelatin actuator naturally biodegrades in outdoor conditions.

Enzyme Degradation. Collagenase is widely used to degrade gelatin-based materials in both research and industrial settings [35, 54]. In typical protocols, enzyme concentrations range from 0.5–2 mg/ml [32, 50], and here a 2 mg/ml solution was selected. McKibben actuator samples were immersed in this collagenase solution for 4–5 days, which is recorded by using a camera, shown by Figure 9b. The relatively extended degradation period—compared to rapid breakdown observed in thin gelatin films [53]—highlights the influence of material geometry and thickness on overall enzyme accessibility and hydrolysis rates.

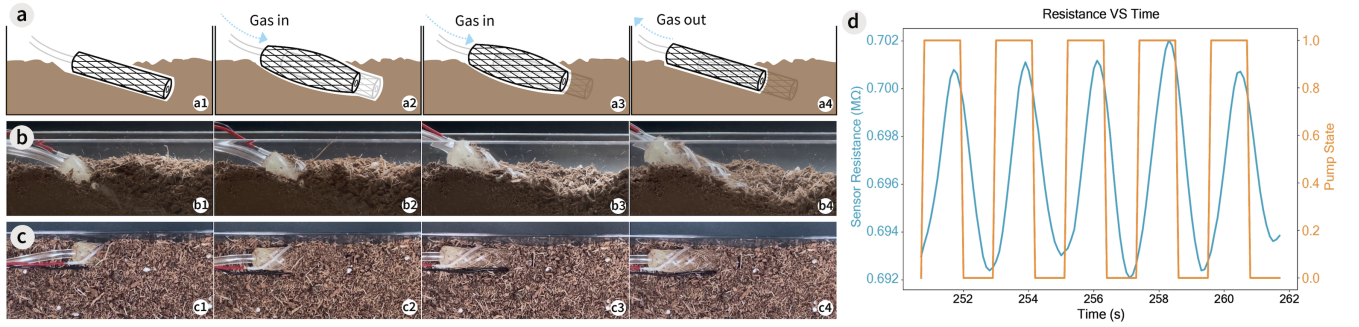


Figure 10: Soil robot actuation and sensing performance. (a) Schematic illustrating the movement mechanism of the soil robot. (b) Side view of the actuator emerging from soil. (c) Top view of the actuator emerging from soil. (d) Comparison of strain sensor resistance changes corresponding to gas pump activation states.

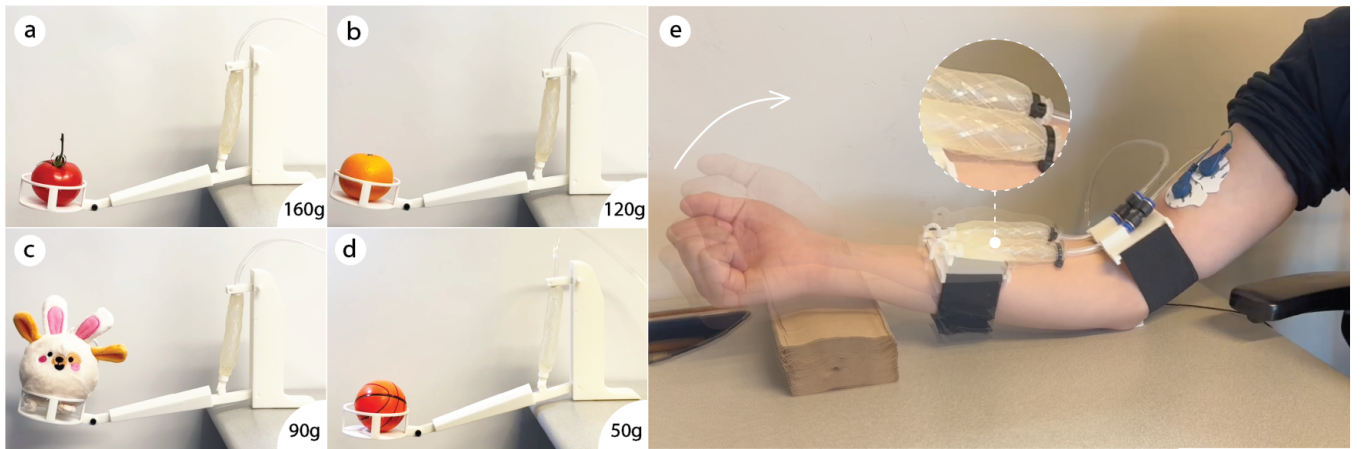


Figure 11: Artificial muscle demonstrations. Actuator attached to a 3D-printed skeletal arm lifting objects of different weights: (a) tomato (160 g), (b) orange (120 g), (c) doll (90 g), and (d) elastic ball (50 g). (e) Wearable device employing two actuators to simulate biceps-assisted motion.

6 APPLICATION

We demonstrate BIOGEM across a series of practical and creative scenarios, highlighting the environmental degradability, wearable integration, interactive sensing, and edible compatibility of our gelatin-based McKibben actuators.

6.1 Soil Bot

To demonstrate the mobility and sustainability of BIOGEM, we introduce a soil bot, highlighting the actuator's ability to navigate through soil and its potential for enhancing agricultural sustainability.

Subterranean mobility is essential for environmental monitoring, underground exploration, and targeted delivery beneath soil surfaces. Our gelatin-based actuator achieves subterranean locomotion through a straightforward operational principle, illustrated in Figure 10a. This process consists of four main steps: First, the actuator is initially placed beneath the soil surface. Upon pressurization, it expands radially, pushing the surrounding soil outward, while simultaneously contracting axially to create a small cavity behind it. Next, soil naturally fills the cavity due to gravity. When

depressurized, the actuator attempts to revert to its original length but encounters resistance from the soil-filled cavity, producing a forward thrust through the reaction force from the soil. Repeating this cycle enables the actuator to gradually move through the soil, as demonstrated in Figure 10b and c. Such mobility is particularly beneficial for operations requiring minimal environmental disruption or navigation within delicate subterranean ecosystems.

As shown in Figure 1b, the actuator is buried beneath the soil, where radish seeds germinate and sprout above ground within a few days. The seeds are embedded on the biodegradable surface of the actuator prior to burial. As the actuator decomposes naturally underground, it eliminates the need for retrieval and reduces labor and waste. This application demonstrates how biodegradable soft robotics can support sustainable agriculture by enabling in-soil seed delivery with minimal environmental disruption.

6.2 Artificial Human Muscle

Similar to conventional McKibben actuators, our biodegradable actuators are capable of functioning as artificial muscles, highlighting

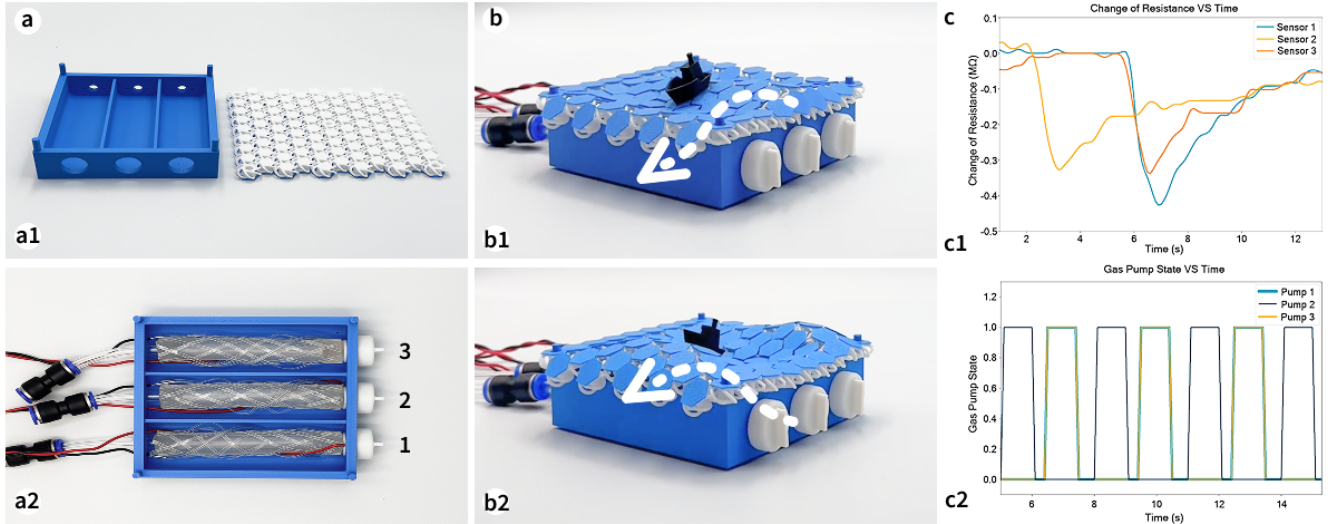


Figure 12: Interactive desktop wave simulator. (a) System components: (a1) base platform with PLA-printed wavy cover, (a2) three embedded actuators connected to tubing and rotating knobs. (b) Demonstration of wave deformation sequences: (b1) "0-1-0" (actuator 2 inflated), (b2) "1-0-1" (actuators 1 and 3 inflated). (c) System response data: (c1) sensor resistance change versus time, (c2) gas pump activation state versus time.

their potential in assistive and wearable technologies. To demonstrate this, we develop both a wearable system and a skeletal lifting rig to mimic the role of the human biceps.

We constructed a 3D-printed skeletal arm resembling human anatomy to evaluate the actuator’s lifting capabilities. A single actuator is mounted on the biceps position and used to lift objects of varying weights. As shown in Figure 11a-d, the actuator successfully lifts a tomato (160g), an orange (120g), a doll (90g), and an elastic ball (50g).

Gaining insights from the above examples, we further implemented two actuators on the human body as an artificial muscle. Shown in Figure 11e, two actuators are mounted at the elbow joint, connecting the forearm to the upper arm. When pressurized, both actuators contract simultaneously, generating force that assists in lifting the forearm—mimicking the motion of the biceps.

To further demonstrate the material tunability and high force output of BIOGEM, we developed a biodegradable gripper using multiple gelatin formulations. As shown in Figure 1b, this is a scissor-like gripper that closes at the front when the rear-mounted actuator contracts. It’s compatible with different actuators and achieves blocking forces ranging from 6N to 25.5N, using a 2:1 rear-to-front lever arm ratio.

6.3 Interactive Desktop Wave Simulator

To further illustrate the sensing capabilities and ease of control of our actuator, we developed an interactive desktop wave simulator, shown by Figure 12. This ocean-themed interactive device mechanically simulates sea waves, providing users with a playful and engaging desktop experience. The device features a PLA-printed wavy cover inspired by NASA’s publicly available fabric design [45] and includes a small PLA ship [52] placed on the surface to enhance the visual experience.

Typically, the application of McKibben actuators emphasizes their axial contraction capabilities while overlooking their equally important radial expansion. Our interactive desktop wave simulator specifically utilizes this radial expansion property. When pressurized, the actuator expands radially, interacting with the flexible, wavy cover to generate realistic wave-like motions.

As shown in Figure 12a, the system includes a modular housing (a1) and three actuators in parallel and connected to tubing and rotating knobs (a2). Users interact directly with the device by twisting these knobs, causing the actuators to twist and deform. Integrated strain sensors wrapped around the actuators detect these movements, allowing for responsive user control. In the "recording mode," users manually rotate each actuator knob in a desired sequence to establish a custom wave pattern. Once the recording is complete, the actuators automatically replay this programmed sequence, offering continuous interactive feedback. Figure 12b illustrates a mixed wave sequence composed of two alternating stages: b1 shows the "0-1-0" activation state, and b2 shows "1-0-1." These two stages cycle continuously to generate rhythmic surface deformation. The corresponding resistance responses from the embedded strain sensors are shown in Figure 12c. Subfigure (c1) shows changes in resistance from each of the three sensors during actuator activation, while (c2) displays the corresponding gas pump activation states over time, indicating which actuators are inflated during the sequence.

This interactive desktop wave simulator showcases the interactive potential of our actuator technology. It emphasizes the importance of radial expansion in McKibben actuators and highlights how user-friendly control and integrated sensing can enhance user engagement and accessibility.

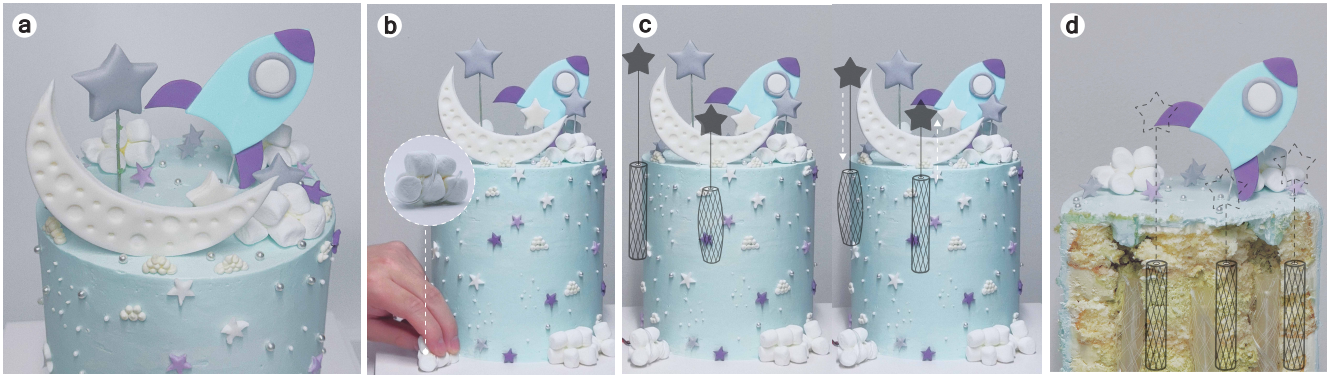


Figure 13: Edible interactive cake. (a) Full view of the space-themed edible interactive cake. (b) Interactive scene showing a hand squeezing the marshmallow interface, with a zoomed-in view of the embedded gelatin-based sensor. (c) Dynamic visual effect of star movement when the system is activated. (d) Section view revealing the location of actuators inside the cake.

6.4 Edible Interactive Cake

Given that our actuator is fully made from edible ingredients, including gelatin, sugar, glycerol, and water, we explore its potential in creative culinary applications. Notably, our actuators possess a pleasant taste reminiscent of gummies, with sweetness primarily derived from their sugar content. Inspired by these edible qualities, shown by Figure 13a, we developed an edible interactive cake that uniquely combines food with interactive technology to offer an engaging and memorable culinary experience.

Traditionally, food presentations are static, offering limited sensory interactions beyond taste and visual appearance. By integrating our edible actuators, we can transform conventional, static culinary creations into dynamic, interactive experiences, all while remaining completely edible and safe for consumption. This approach significantly broadens the sensory appeal and interactive potential of food, providing users with unique and memorable dining interactions.

To create an intuitive control interface, we designed a marshmallow cloud embedded with gelatin-based strain sensors. This interaction is illustrated in Figure 13b, where a gentle squeeze or twist of the marshmallow causes resistance change of the sensor and activates the actuator system. When activated, pneumatic pressure is converted into mechanical motion, making the chocolate stars on top of the cake rise and fall in a rhythmic motion. This dynamic visual effect can be seen in Figure 13c, where the animated movement brings the cake to life and enhances the sensory experience.

This edible interactive cake showcases the innovative possibilities of our biodegradable actuator technology, extending its applications beyond traditional robotics into creative culinary and interactive art contexts. Such demonstrations underscore the novelty and significance of sustainable, edible interactive systems, presenting an environmentally friendly alternative to conventional electronic or plastic-based interactive installations.

7 LIMITATIONS AND FUTURE WORK

While our fully biodegradable actuator and sensing system demonstrates promising functionality, several limitations highlight areas for improvement and future exploration.

Mechanical Fragility and Environmental Sensitivity. The gelatin-based composites used in our actuators are highly sensitive to environmental conditions, particularly humidity and temperature. Although these properties contribute to biodegradability, they also reduce long-term stability in uncontrolled or outdoor environments. High humidity can accelerate softening, while low humidity may lead to brittleness or cracking. Future work could investigate biocompatible coatings or composite blends that preserve degradability while improving mechanical robustness.

Sensor Noise and Drift. Our ionic gelatin-based sensors operate at high resistance levels and are prone to hysteresis and baseline drift. While adequate for detecting trends in deformation, this limits their precision in real-time control scenarios. Future directions include integrating drift compensation algorithms or developing hybrid biodegradable materials with more stable conductive behavior.

Actuating Force Range. Compared to industrial McKibben actuators, achieving the high pressures of conventional designs is impractical for biodegradable materials due to the limited mechanical strength of biodegradable inner tubes and current design constraints. By replacing synthetic fibers with rigid gelatin strips, our actuator operates at lower pressures, yet delivers comparable payloads (8N) and significantly higher contraction within its intended range (10% at 13 kPa vs. 1% at 100 kPa for conventional actuators [31]). However, its overall contraction ratio and force output remain modest compared to conventional synthetic actuators. Future work may explore multilayer composites, reinforcement strategies, or alternative geometries to enhance actuation power while maintaining full compostability.

8 CONCLUSION

We present a fully biodegradable soft actuator system that integrates both mechanical actuation and strain sensing using gelatin-based materials. Our approach shows how sustainable composites,

carefully customized through material formulation and structural design, can enable pneumatic motion and embedded sensing without relying on traditional synthetic polymers or electronic components. Through systematic testing, we explore how design parameters such as braid angle, wall thickness, Young's modulus, and NaCl concentration influence the actuator and sensor performance. We demonstrate that the system maintains reliable behavior over repeated cycles and identify practical trade-offs relevant to soft interactive systems. This platform opens new possibilities for applications such as environmentally responsible wearables, temporary deployable robots, and biodegradable interactive artifacts. These results suggest that biodegradable actuators can achieve meaningful functionality while aligning with sustainability goals. This work contributes to the broader effort in HCI and soft robotics to rethink how interactive systems are made, used, and decomposed. By developing a fully compostable and responsive actuator platform, we hope to inspire future research in sustainable design, sensing, and embodied interaction.

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