

*Research Article*

Self-Healing Actuators Inspired by Locomotion of Unicellular Organisms

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Abstract: Diverse locomotion mechanisms in nature enable organisms to navigate unfavorable environments, ensuring their survival and propagation. This study proposes the fabrication and characterization of a bio-inspired actuator based on the flagellar locomotion of single-celled organisms within the Eukarya domain. Subsequently, the design was refined for enhanced controllability and facile fabrication. The actuator leverages the eukaryotic locomotion principles while uniquely incorporating self-healing properties inspired by the cell wall structures of bacteria and eukarya. This actuator is fabricated from a composite hydrogel of gelatin, silk amino acids, glycerol, and deionized water and is a sustainable alternative to conventional silicone-based materials. The self-healing composite exhibited an elongation at break of $156.8 \pm 5.7\%$; the bending angle of the assembled actuator recovered by approximately 58% after puncture and healing. This work provides the inspiration for novel robotic designs and propulsion systems with specialized functionalities, potentially expanding soft robotics' operational boundaries.

Keywords: Living organisms; Natural materials; Robotics; Self-healing component

1. Introduction

Conventional robotic development heavily relies on motors for actuation and rigid materials, such as metals, plastics, and composites, for structural components (Licardo et al., 2024; Yang & Hu, 2023). However, when considering natural organisms that originated on Earth before robots, various locomotion methods do not require the use of electric motors. Furthermore, biological structures are not exclusively rigid. They are often composed of soft, compliant materials, a concept that has been extensively integrated into the development of modern soft robots (Bliah et al., 2025; Eyvazian et al., 2026; Wang et al., 2025). They possess the remarkable ability to self-heal, restoring near-original functionality after sustaining damage. Therefore, bio-inspired robotic design represents an opportunity to learn from an experienced entity that has already proven its ability to survive. This approach will result in the expansion of the working scope for the next generation of robots (Ashuri et al., 2020; Chen et al., 2026; Jeong et al., 2025). Applications include navigating environments with electrical or electronic constraints and deploying robots in high-risk scenarios where damage is likely and subsequent repair is infeasible. The natural world is immensely diverse, and organisms are classified into numerous categories. This study focuses on unicellular organisms, which represent some of the earliest forms of life on Earth. Unicellular organisms exhibit various methods of motility. Organisms in both the Bacteria and Eukarya domains commonly possess a locomotive organelle with a similar name: the flagellum. The bacterial flagellum is rotated by a membrane-anchored basal body that functions analogously to a direct current (DC) electric motor, whereas the eukaryotic flagellum generates motion without any rotary element (Berg, 2011; Nakamura & Minamino, 2024). Because rotary actuation is precisely what conventional robots already provide, this study adopts the eukaryotic mechanism instead. Eukaryotic flagella are driven by the axoneme, a microtubule structure arranged in a canonical 9+2 pattern (9 peripheral doublets and 2 central microtubules) for locomotion, as shown in Figure 1 (Mitchell, 2007). The axoneme moves through localized

bending rather than rotation caused by dynein motors sliding along microtubules. This bending mechanism serves as a bio-inspired model for our actuator. Additionally, unicellular organisms exhibit remarkable self-healing capabilities, such as surviving severe physical damage (del Valle et al., 2020; Suo et al., 2009).

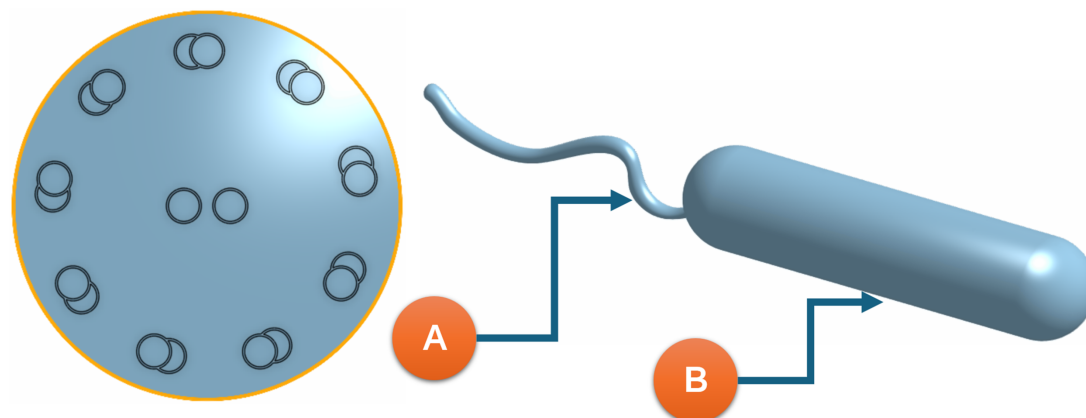


Figure 1 Schematic cross-section of the eukaryotic axoneme, illustrating the canonical arrangement of 9 + 2. Black outlines represent the microtubules, and the red outline indicates the cell membrane. (A) Schematic of a bacterium possessing a single flagellum. (B) The cell body

Existing soft grippers based on pneumatic bending actuators are typically constrained to a single bending plane, flexing inward to grasp and outward to release, which restricts end-effector trajectories to two directions (Chen et al., 2023; Kashef Tabrizian et al., 2023). In contrast, flagellum-inspired actuators demonstrate significantly richer motion capabilities, but they do not incorporate self-healing functionality (Miao et al., 2023). In this study, the 9+2 axoneme structure is engineered into three independently controlled pneumatic chambers. This design enables three-dimensional end-effector control beyond the single-plane bending of conventional grippers, a capability that could enable tasks such as unscrewing a bottle cap. The actuator is fabricated entirely from a bio-derived gelatin–silk amino acid–glycerol composite. Unlike many existing self-healing soft actuators, this composite heals at room temperature without thermal or photochemical activation or specialized mixing equipment. Together, these characteristics make the actuator highly suited for pressurized-fluid applications (such as air or water) where punctures, tearing, and leakage are likely to occur. Relative to previously reported self-healing materials (Tabrizian et al., 2022), the present system emphasizes material and processing simplicity over absolute recovery, while also offering straightforward fabrication into actuators. Prior studies generally report higher healing efficiencies, typically in the range of 95% (Huang et al., 2022; Li et al., 2024). Recovery is also relatively rapid, often within 8–45 minutes. However, these systems rely on external triggers (Peng et al., 2022; Raman et al., 2024; Tan et al., 2022; Wang et al., 2021). In contrast, the actuator reported here heals autonomously at room temperature from an entirely bio-derived composite without any external stimulus, albeit with a lower functional recovery.

2. Materials and Methods

2.1 Actuator design

The materials used to construct the actuator are divided into two parts: a strong material that serves as a substitute for the cell wall in living organisms and a self-healing material that represents the layer located just inside the cell wall (Tang & Marshall, 2017). However, the design will be modified to focus on developing materials that do not require special preparation or specialized equipment for mixing.

Although numerous actuation methods are available in electrical stimulation, chemical reactions, cable-driven systems, or pneumatics, a pneumatic system is employed in this study. This choice was made to emulate the dynein-driven sliding mechanism that causes the characteristic bending of the eukaryotic axoneme, replacing biological sliding with pneumatic inflation (Höög et al., 2014). The primary objective of this study is to investigate the expanded operational scope of this actuator, particularly for applications such as soft grippers, handling sharp objects, and locomotion in hazardous environments where the risk of puncture, tearing, and leakage is high. The design was simplified to reduce the complexity of the pneumatic control system and minimize the number of required air tubes while retaining the essential flagellar motion. Instead of actuating all 9 peripheral microtubule pairs independently, they were conceptually bundled into three distinct, independently controlled groups. Therefore, each group comprises three of the original microtubule pairs.

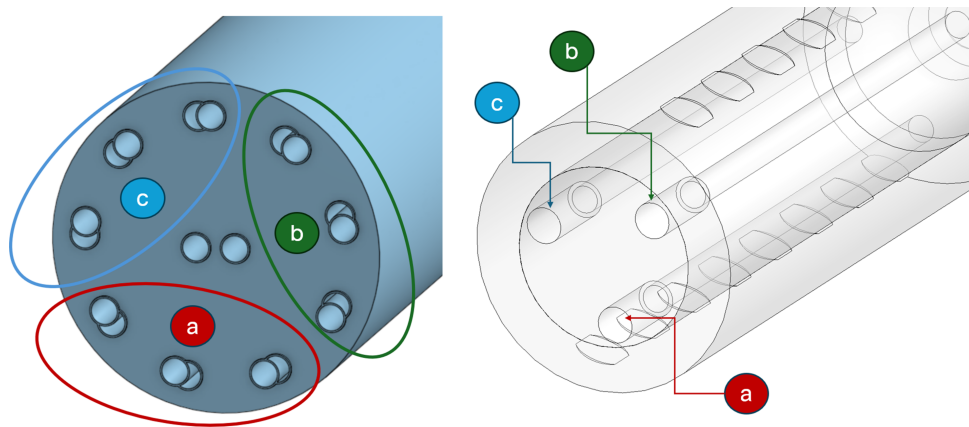


Figure 2 Schematic comparison of the fabricated actuator cross-section (right) with its biological inspiration, the eukaryotic axoneme (left). The 9 peripheral microtubule doublets are divided into three groups of three, each reduced to one independently controlled pneumatic chamber: (a) red, (b) green, (c) blue. The same label marks the same group on both sides.

The proposed configuration facilitates versatile and precise 3D control of the actuator's end-effector. For example, when applied as the legs of a robot with three or more legs, it allows the robot to change its movement direction while remaining in the same position. Alternatively, it could be implemented as a robotic gripper; for instance, a two-fingered gripper could be used to open a water bottle cap. This level of control is achieved by modulating the air pressure in each channel to induce the desired bending vector (Edward & Golecki, 2023).

2.2 Preparation of the outer structural material (outer cell wall layer)

Gelatin and glycerol, the basic ingredients, can produce a material with good strength (Baghali et al., 2023; Hardman et al., 2022). The preparation protocol involved combining bovine gelatin, deionized water, and glycerol in a beaker. The mixture was heated to 60°C and stirred with a glass rod until the gelatin was fully dissolved. Six distinct weight ratios were prepared and compared to determine the optimal formulation, as shown in Table 1.

The selected ratio results in a material with sufficient mechanical strength to support the actuator's own weight, particularly for robotic leg applications. After mixing, each formulation was poured into the Petri dishes for observation. The optimal formulation was selected based on three criteria: ease of fabrication (mixability), flexibility (elongation), and storage stability (microbial growth resistance).

- **Easy to Fabricate:** Formulations S1, S2, and S6 were difficult to process. They exhibited poor miscibility, and significant undissolved gelatin crystals remained after stirring. In contrast, S3, S4, and S5 achieved homogeneous mixtures.

Table 1 Weight ratios of the outer structural material formulations (Gelatin:Deionized Water:Glycerol)

Formulation	Gelatin : Deionized Water : Glycerol	Elongation Rank	Easy to fabricate
S1	40:10:50	6	poor
S2	40:20:40	5	poor
S3	40:30:30	3	good
S4	40:40:20	2	good
S5	40:50:10	1	good
S6	40:0:60	4	poor

- **Storage Stability:** After 100 hours of storage at ambient room temperature (in a room with open-window ventilation) with an average relative humidity of 75%, samples S4 and S5 exhibited visible mold growth on the surface. S3 did not show any contamination within this timeframe.
- **Flexibility:** Tensile testing was conducted in accordance with the ASTM D412 standard to evaluate the mechanical properties of the composite materials. Three independent specimens ($n = 3$) were tested for each material formulation (designated as S1 through S6, where S3 represents the primary structural material of the actuator) to ensure repeatability. The flexibility of the composite materials was assessed quantitatively based on their elongation at break. Formulation S5 exhibited the highest flexibility, achieving a maximum elongation of $187.6 \pm 1.0\%$. The primary structural material, S3, provided an optimal balance of flexibility and structural integrity necessary for the pneumatic chambers' bending mechanism, exhibiting an elongation of $143.8 \pm 5.5\%$. In contrast, formulation S1 exhibited the most rigid behavior, with an elongation of only $32.7 \pm 1.9\%$.

Based on this comparative analysis, S3 was selected as the optimal structural material. It provided the best balance of homogeneous fabrication, adequate flexibility, and short-term stability against microbial contamination.

For future development, the addition of organic acids, such as citric acid, has been shown to inhibit bacterial growth in similar biopolymer composites, a preservation principle also observed in natural substances such as honey (Mandal & Mandal, 2011).

2.3 Preparation of the self-healing material (self-healing layer)

Silk amino acid composites (Liu et al., 2019; Thirumalai et al., 2024), particularly when combined with gelatin or glycerol, are known to exhibit self-healing properties (Liu et al., 2022; Lyu et al., 2022). This capability is attributed to the formation of dynamic chemical bonds (e.g., hydrogen bonds) involving the amino acid functional groups within the silk amino acid structure and other matrix components (Mushtaq et al., 2025; Thirumalai et al., 2024). This study experimented with various formulations of gelatin, silk amino acids (silk amino acids mixed with DI water at 0.15 wt%), and glycerol to develop a material with healing capabilities. The self-healing layer was prepared using the same protocol as the structural material: the ingredients were combined in a beaker according to the specific weight ratios shown in Table 2, then heated to 60°C and stirred with a glass rod until fully dissolved.

These formulations were part of an initial random screening process to identify a self-healing material based on a starting blend of gelatin and silk amino acids. SH5 was selected as the optimal self-healing formulation with an elongation at break of $156.8 \pm 5.7\%$. For SH5, a shallow surface incision closes within 12 h at room temperature (Figure 3), whereas a fully severed channel barely rejoins under the same conditions.

Table 2 Weight ratios of the self-healing material formulations (Gelatin:Silk amino acids:Glycerol)

Formulation	Gelatin : Silk amino acids : Glycerol	Healing	Easy to fabricate
SH1	10:60:30	poor	good
SH2	20:56:24	poor	good
SH3	30:49:21	poor	good
SH4	40:30:30	poor	poor
SH5	40:42:18	good	good

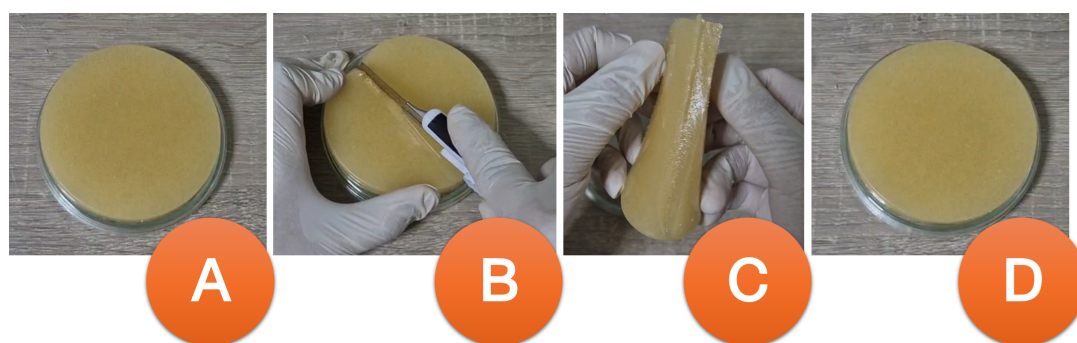


Figure 3 Demonstration of the self-healing capability of SH5. (A) As-prepared material sample after demolding. (B) The sample is intentionally incised with a cutter blade. (C) Close-up view of the incision, penetrating approximately 2/3 of the depth of the material. (D) The same sample after 12 h of healing at room temperature, showing the closure of the shallow incision. Under these conditions, healing plateaued within 12 h; extending the rest period to 72 h produced no further improvement

2.4 Fabrication and assembly of actuators

The actuator was fabricated using a 4-part mold, which was 3D printed from polylactic acid (PLA) material (Figure 4). The mold components were assembled using 304 stainless steel screws and nuts. The casting protocol was as follows:

- **Structural layer casting:** Mold parts A and B were assembled. The structural material (S3, prepared as described in Section 2.2) was allowed to cool for 15 minutes while it was still liquid. The mixture was then carefully poured into the A–B assembly. (Note: This step is time-sensitive due to the rapid gelation of the material).
- **First gelation:** Mold part C was immediately placed on the assembly top and secured with screws to prevent misalignment. The material was allowed to form a gel (10 minutes for the prototype volume).
- **Self-Healing Layer Casting:** After gelling the structural layer, the screws securing part C were removed, and part C was demolded. The self-healing material (prepared as described in Section 2.3) was then poured on top of the gelled S3 layer.
- **Second gelation:** Mold part D was assembled similarly to part C, and the composite was allowed to gel completely.
- **Demolding and curing:** All mold components were disassembled, and the actuator was carefully demolded. The completed actuator was left to cure at ambient temperature for 12 hours, during which minor shrinkage was observed.

- **Final Assembly:** The cured actuator was mounted onto an acrylic base. Pneumatic tubes were connected, and all components were permanently affixed using polyvinyl chloride adhesive.

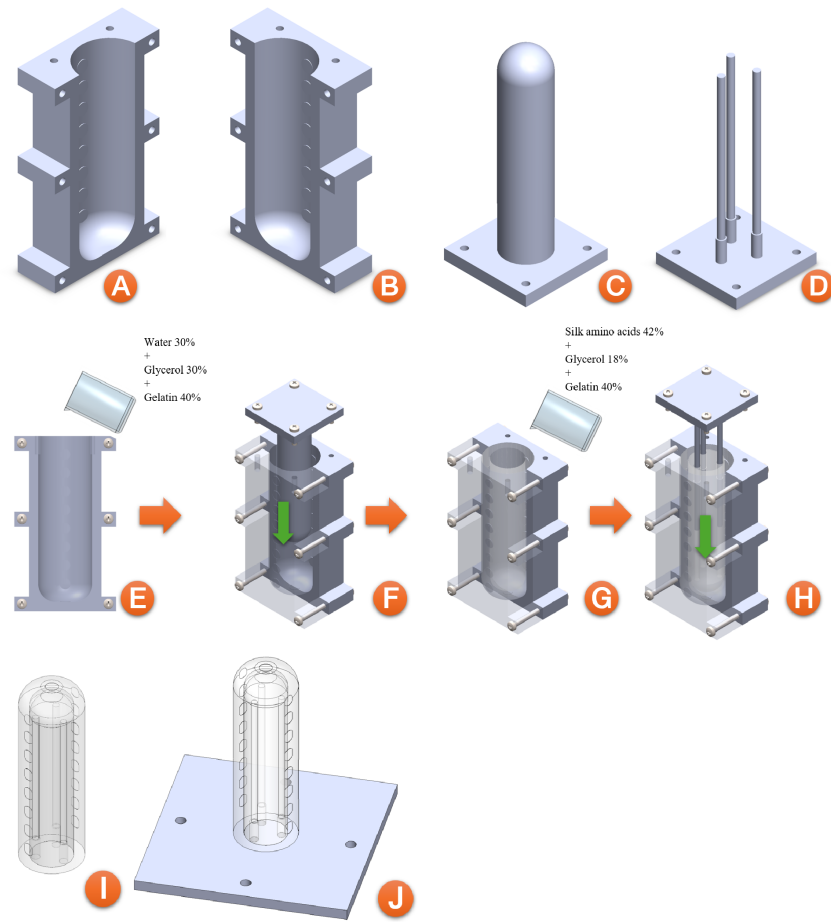


Figure 4 Multi-step fabrication and casting process of the actuator using the 4-part 3D-printed mold. (A) Mold Part A. (B) Mold Part B. (C) Mold Part C (Inner core for the structural layer). (D) Mold Part D (Inner core for the self-healing layer). (E) Assembly of Parts A and B, followed by casting of the structural material (S3). (F) Assembly of Part C. (G) Part C demolding and casting of the self-healing material. (H) Assembly of Part D. (I) Fully cured, demolded actuator. (J) Final actuator mounted on the test rig

2.5 Pneumatic Control System (PCS)

Pneumatic pressure was generated and controlled using a custom syringe pump (Supriyanto et al., 2021). This apparatus consists of a stepper motor that drives a standard syringe and is mechanically coupled to a lead screw and bushing assembly. The stepper motor's rotation is converted into linear displacement of the lead screw, which precisely pushes or pulls the syringe plunger. This action changes the “dead volume” of the system, forcing air molecules into the actuator channels (inflation) or drawing them out (deflation). The behavior of this system is described by the following relationships: The linear displacement of the plunger (ΔL) related to the stepper motor rotation angle (θ) is given as follows:

$$\Delta L = \frac{p \cdot \theta}{360} \quad (1)$$

where $\Delta L = L_1 - L_2$.

L_1 = Initial distance inside the syringe barrel (m)

L_2 = Final distance inside the syringe barrel (m)

p = Lead of the lead screw (0.002 m/revolution)

θ = Rotation angle of the stepper motor ($^\circ$)

An isothermal process is assumed for the pressure-volume relationship of the closed system (syringe + tubing + actuator channels):

$$P_2 = P_1 \frac{V_1}{V_2} = P_1 \left(\frac{V_1}{V_1 - (A \cdot \Delta L)} \right) \quad (2)$$

where:

P_1, V_1 = Initial pressure and total volume of the system, respectively

P_2, V_2 = Final pressure and total volume of the system, respectively

The change in volume $\Delta V = V_1 - V_2$ is a function of the plunger displacement (ΔL) and the syringe cross-sectional area (A). Therefore, the final pressure (P_2) in the system can be precisely controlled by controlling the stepper motor rotation angle (θ).

2.6 Acquisition of actuator position data

Eight circular markers (3 mm diameter) were affixed in a linear array along with the lateral profile of the specimen to quantify the actuator kinematics. A high-resolution camera was positioned to capture a lateral (side-view) video feed of the actuator during operation. The video was processed using the OpenCV library to perform real-time tracking of each marker's centroid. With this configuration, the end-effector position could be accurately determined while fully characterizing the actuator bending behavior. The resulting deflection was plotted as a 2D trajectory upon pneumatic stimulation, while the coordinates of all eight markers were used to reconstruct the actuator body's curvature. The tracking system demonstrated a positional accuracy of ± 0.2 mm.

3. Kinematic Model for the Actuator

This section introduces the self-healing actuator's kinematic model. The corresponding coordinate frames for the self-healing actuator are described using a piecewise universal joint approach adapted from the Piecewise Constant Curvature (PCC) model (Santina et al., 2023; Wang et al., 2023). In this study, the model variables include a translation from the base ($\hat{Z}_0$) to the arc center of the self-healing actuator ($\hat{Z}_1$) by a distance l_1 . The rotation at the arc center is modeled as a universal joint, represented by θ_1 and θ_2 , respectively. Finally, the transformation concludes with a translation from the arc center to the end-effector of the actuator by a distance l_2 , the precision of this model can be enhanced by increasing the number of segments (Figure 5), corresponding to the distance between each black point shown in Figure 6. The resulting homogeneous transformation matrix is given as follows:

$$T_0^e = \begin{bmatrix} c_{\theta_2} & 0 & s_{\theta_2} & l_2 s_{\theta_2} \\ s_{\theta_1} s_{\theta_2} & c_{\theta_1} & -s_{\theta_1} c_{\theta_2} & -l_2 s_{\theta_1} c_{\theta_2} \\ -c_{\theta_1} s_{\theta_2} & s_{\theta_1} & c_{\theta_1} c_{\theta_2} & l_1 + l_2 c_{\theta_1} c_{\theta_2} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

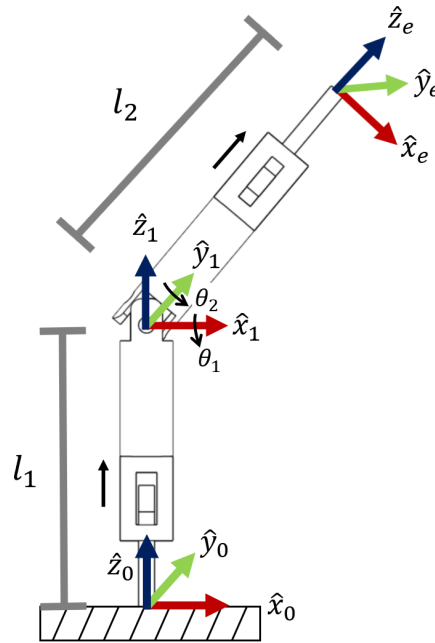


Figure 5 Kinematic representation of the single-segment piecewise universal joint (PUJ) model: two prismatic joints and one universal joint. The black straight arrows show the direction of the prismatic joints, of length l_1 from the base frame ($\hat{x}_0, \hat{y}_0, \hat{z}_0$) to the arc-centre frame ($\hat{x}_1, \hat{y}_1, \hat{z}_1$) and of length l_2 from the arc centre to the end-effector frame ($\hat{x}_e, \hat{y}_e, \hat{z}_e$). The angles θ_1 and θ_2 are the two orthogonal rotations of the universal joint. Red, green and blue arrows denote the $\hat{x}$, $\hat{y}$ and $\hat{z}$ axes

4. Results and Discussion

4.1 Testing of the composite actuator (outer cell wall and self-healing layer)

The fabricated actuator successfully demonstrated controllable bending upon pressurization. When a single pneumatic channel was inflated, the actuator's end-effector deflected in one of the three primary directions (oriented 120° apart, corresponding to the channel layout). Motion in other directions can be generated by adjusting the pressure within each tube. A critical observation was made during the over-pressurization testing (conducted on 3 independent specimens). At a maximum achievable pressure of 214 kPa, the specimen experienced catastrophic failure (rupture), resulting in a leak. After a 12-h resting period, the inner self-healing material repaired the tear. However, the system could sustain approximately 8% of the original pressure capacity before tearing occurred again. In a separate test ($n = 3$), a single channel was deliberately and completely incised (cut). After a 12-hour healing period, the channel healed and could withstand 16% of its original operational pressure before failure.

4.2 Homogeneous self-healing actuator testing

Given that the previous tests confirmed that the structural material (S3) did not possess self-healing properties, a homogeneous actuator was fabricated only from the self-healing material (i.e., the structural layer casting step was omitted). This homogeneous actuator demonstrates extreme resilience. It could not burst because it could withstand pressures exceeding the maximum output of the pneumatic control system (214 kPa). In terms of kinematic performance, the actuator achieved a maximum deflection of 25.62° from the horizontal plane when two channels were simultaneously pressurized to 214 kPa. One tube was intentionally severed during the cutting test to evaluate damage tolerance ($n = 3$). Subsequently, the system sustained approximately 33% of the original pressure capacity compared to the pre-cut condition. Furthermore, ten additional specimens ($n = 10$) were prepared and subjected to a puncture test to assess

operational repeatability under continuous usage. A scalpel was used to directly inflict a penetrating wound into the pneumatic channel. The specimens were then allowed to self-heal for 12 hours. The actuators were then subjected to a cyclic actuation test using an applied pressure of 80 kPa for 50 continuous bending cycles. The bending angle before and after the puncture was recorded and compared to evaluate the recovery of kinematic performance. All angles were measured during the first actuation cycle.

Of the 10 specimens, one actuator experienced a leak after 13 cycles, and the other failed after 49 cycles. For the remaining eight specimens that underwent the 50-cycle test, the average bending angle before being damaged was 6.65 ± 1.16 degrees. The recovered bending angle after self-healing was 3.88 ± 0.42 degrees, corresponding to a recovery of approximately 58% of the original bending angle. The reduction in bending angle after healing indicates that the healed channel did not fully restore its original bending capability. Further testing of healed specimens is needed to characterize this effect.

The kinematic model was validated against the measured marker positions of these eight specimens at 80 kPa, across peak bending angles ranging from 5.1° to 10.3° . The curvature was estimated from the distal marker, and the six intermediate markers were then reconstructed from the Piecewise Universal Joint model as an out-of-sample evaluation, since these markers were not used in the estimation. The model reproduced the measured shape with an RMSE of 0.263 mm and $R^2 = 0.985$, which is comparable to the ± 0.2 mm tracking accuracy. A regression slope of 0.941 indicates a slight under-prediction at larger angles, which is expected to decrease with more segments. These results confirm that the single-segment PUJ model provides an accurate and compact kinematic description of the actuator (Figure 6).

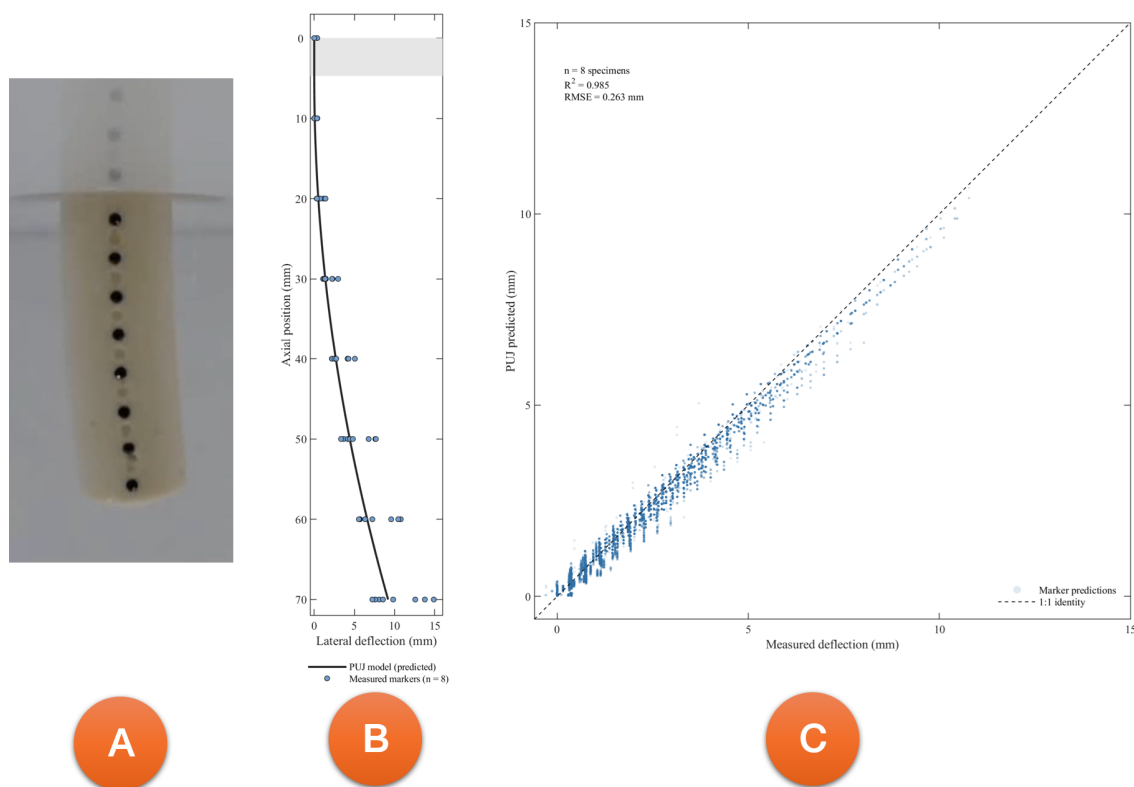


Figure 6 Validation of the single-segment PUJ model (planar case, $\theta_2 \approx 0$). (A) Specimen bending during actuation. (B) Predicted profile (line) and measured marker positions (circles) for eight specimens; the shaded band marks the proximal rigid length $l_1 = 4.71$ mm. (C) Out-of-sample predicted versus measured deflection ($n = 8$); the dashed line is the 1:1 identity, giving $R^2 = 0.985$ and RMSE = 0.263 mm

5. Other Properties of the Material

Another important property of the material is its ability to conduct electricity. Beyond the chemo-mechanical and self-healing properties, both the structural material (S3) and the self-healing composite (Gelatin: Silk amino acids: Glycerol) exhibited inherent electrical conductivity. This is a highly advantageous characteristic for robotic applications, particularly for the development of self-healing sensors. A primary challenge in resilient robotics is that a self-healing actuator is of limited use if its integrated sensors fail permanently after damage (Tadesse & Lübben, 2023). To address this, we explored the potential of our self-healing material to function as a piezoresistive strain sensor (Wang et al., 2020). The self-healing composite was fabricated into a thin rectangular sheet for preliminary characterization. When the material is stretched or bent, its electrical resistance changes, making it a viable candidate for a strain or bend sensor. Quantitative sensor characterization (resistance–strain response and gauge factor) is beyond the scope of this study and is left for future work. The material was found to be self-adherent to human skin yet easily removable as an interesting secondary property.

The integration of such a sensor with our actuator would create a fully proprioceptive system. This would be invaluable for detecting operational failures such as an inability to bend caused by a puncture or cutting signal, signaling that physical damage has occurred and that a healing cycle is required.

6. Conclusions

This study demonstrated a bio-inspired pneumatic actuator with a self-healing layer fabricated from a bio-derived gelatin–silk amino acid–glycerol composite (SH5, 40:42:18) that heals at room temperature without thermal or photochemical activation. Two configurations were evaluated. In the composite configuration, where the self-healing layer is combined with the S3 structural layer, the actuator recovered only approximately 8% and 16% of its original pressure capacity after rupture and a full channel cut, respectively. The main failure mode was identified as localized inflation at the layer interface, followed by air penetration along the seam. In contrast, the homogeneous actuator fabricated entirely from the self-healing material could not burst below the 214 kPa system limit, retained approximately 33% of its pressure capacity after a tube was severed, and recovered approximately 58% of its bending angle after puncture and healing across eight specimens. The single-segment piecewise universal joint model reproduced the measured shape with $R^2 = 0.985$ (RMSE = 0.263 mm), confirming the compact description of the actuator kinematics. Room-temperature re-bonding plateaued within approximately 12 h and did not improve up to 72 h. The main practical limitations of this method are the partial recovery of mechanical performance after healing and the tacky surface of the self-healing layer, which attracts dust and debris in locomotion or gripping applications.

7. Future Work

Given that the mechanical strength of the current biopolymer composite is closer to that of a soft polymer or hydrogel than to that of a rigid thermoset, the primary direction for future research is material reinforcement. The research team proposes the incorporation of graphene into the biopolymer matrix to create a nanocomposite that significantly enhances the material's tensile strength and stiffness. The successful development of such a nanocomposite would enable the fabrication of robust, functional, and self-healing robotic components, such as load-bearing legs, for practical, real-world applications. In addition, because the self-healing layer is inherently tacky, a thin protective coating will be investigated to prevent dust and debris from adhering during locomotion or gripping without impeding the underlying healing mechanism. Finally, a future direction is to supply the material with an internal fluid system analogous to blood because a fully severed channel does not autonomously rejoin at room temperature. For example, silk amino acid solution could be delivered to the wound site to promote full separation healing.

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Author Contributions

Chawisorn Samrit: Designed the study, developed the methodology, developed the experiments, performed data analysis, and drafted the manuscript. Narongsak Tirasuntarakul: Reviewing and providing guidance on data management and data visualization. Orapadee Joochim: Liaised with field experts, performed comparative analysis of related literature, and conducted final manuscript review.

Conflict of Interest

The authors declare no conflicts of interest.

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