CREATE Lab Semeter Project

Programmable Breakdown in Gelatin-Based Materials for Regenerative Soft Robotics

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1 Introduction

Modern robotics has achieved remarkable advances in locomotion, control, and perception [1]. The vast majority of robots remain physically rigid and structurally static [2]. When damaged, they require human intervention; when a task demands new morphology, some cannot adapt [3]. In contrast, biological organisms grow, repair, and regenerate [4]. Cells divide to heal wounds, plants extend toward light by growing new tissue, and animals can regrow entire limbs. These regenerative mechanisms are not only passive responses but active processes of replacement, plasticity, and repair[4]. These qualities could greatly extend the longevity and autonomy of robotic systems[5].

Recent work has begun to move robotics in this direction[5]. Growing robots, such as those developed by Barbara Mazzolai's group, draw inspiration from plant roots to continuously extrude material at their tips, enabling navigation through complex and confined environments. These robots demonstrate self-extension, but they lack the ability to remove or reshape their existing body[6]. Self-healing materials, explored in soft robots by researchers like Robert Shepherd, enable passive repair through temperature-triggered chemical bonding. These systems can recover from minor damage but cannot reconfigure their structure or selectively regenerate[7]. Reconfigurable modular robots, such as SMORES-EP from the University of Pennsylvania, can rearrange their form using pre-built articulated units. While powerful, they depend on rigid, pre-defined hardware and do not dynamically grow or decompose material[8].

In summary, existing systems provide partial regenerative capabilities—growth, healing, or reconfiguration—but none enable both controlled material breakdown and targeted regrowth[6]–[8]. This work aims to address that gap. Figure 1 illustrates the conceptual progression from rigid robots to fully regenerative soft systems. We explore a new class of material-based regenerative robots that achieve three biological functions in a soft robotic framework: (1) **Replacement**, or regrowing removed parts, (2) **Plasticity**, or adapting body shape through reconfiguration, and (3) **Repair**, or localized self-healing at vulnerable points[6]–[8].

Our approach shifts regeneration from modular hardware design to programmable soft materials. Specifically, we focus on biocompatible gelatin-based composites that can be tuned through additives like cornstarch, glycerol, and the enzyme transglutaminase (TGase) to modify mechanical strength and dissolution behavior [9]. By embedding programmable weak points—regions designed to dissolve or fail faster under stress—we aim to make structures that can break predictably and be regenerated through extrusion.

This draws inspiration from morphogenesis and other biological processes, where form emerges from local rules and material interactions. A robotic system built on this principle could delete and regrow its body structure dynamically, driven by environmental triggers or task demands[4].

In this report, we present an early-stage material exploration phase focused on enabling controllable breakdown as a step toward full regeneration. We screened multiple materials (PVA, Soluvlies, cotton candy, and gelatin) and selected gelatin due to its favorable mechanical and dissolution properties. We experimented with compositional tuning, adding cornstarch and glycerol for structure and flexibility, and TGase for crosslinking[10]. Gelatin bars with central weak segments (pure gelatin) were tested under water and mechanical motion. Additionally, TGase-crosslinked samples were compared to non-crosslinked ones for elasticity and water durability.

Although the extrusion and regrowth mechanism remains under development, our findings show that gelatin-based materials can be engineered to dissolve selectively and resist failure strategically. This foundational insight sets the stage for future integration of active material deletion, and for building regenerative robots that can adapt, repair, and evolve[4].

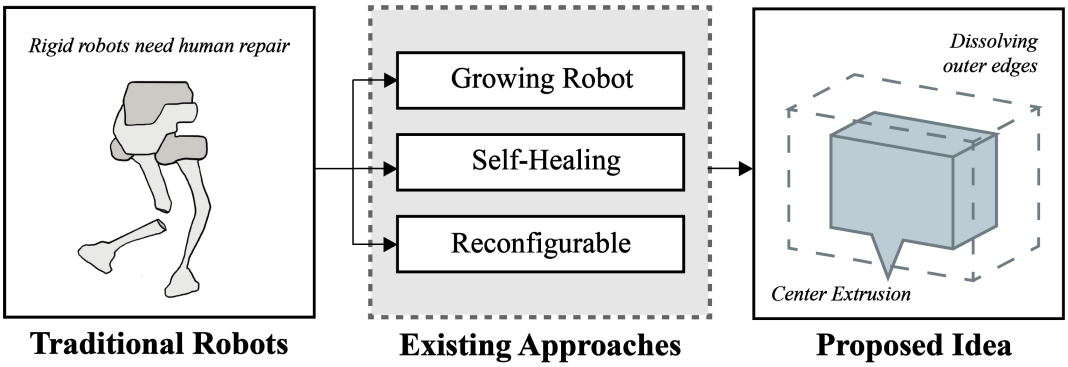

Figure 1: Conceptual overview. (Left) Traditional rigid robots rely on human repair. (Middle) Existing methods offer partial regeneration—growth, healing, or reconfiguration. (Right) Proposed regenerative robot integrates extrusion, dissolution, and programmable morphology.

2 Methods

This study explores the use of programmable material properties in biocompatible gelatin-based structures. The goal was to fabricate soft bars composed of segments with differing mechanical and dissolution characteristics, and to test whether breakdown could be localized to weaker regions [9]. Fabrication and testing were kept at small scale to enable rapid iteration and material efficiency.

Initial screening included polyvinyl alcohol (PVA), cotton candy, and Vlieseline Soluvlies [11]. These materials were ultimately rejected due to undesirable dissolution properties: PVA required high temperatures to dissolve slowly; cotton candy dissolved too quickly; and Soluvlies, being a fabric, lacked formability. Gelatin was selected as the primary material due to its water-responsiveness, moldability, mechanical tunability, and ease of sourcing [10].

Table 1: Material Formulations Tested

Formulation Type	**Composition (mass ratio)**
Strong Segment	Gelatin : Cornstarch = 2 : 1 or 4 : 1
Flexible Formulation	Gelatin : Glycerol : Water = 1 : 1.5 : 2.5
Crosslinked Formulation	Gelatin : Glycerol : Water : TGase = 1 : 1.5 : 2.5 : 0.01

The general fabrication procedure is illustrated in Figure 2. Gelatin sheets were first soaked in cold water, then dissolved in hot water and mixed with additional ingredients depending on the formulation. The mixtures were poured into custom 3D-printed molds and left to cure at room temperature. Final bar lengths ranged from 65 mm to 155 mm. In some samples, a central 20–30 mm segment of pure gelatin was included to act as a predefined weak point. All ingredients were precisely weighed using a digital scale to ensure consistency and repeatability.

3 Experimental Setup

Experiments were organized into three main categories:

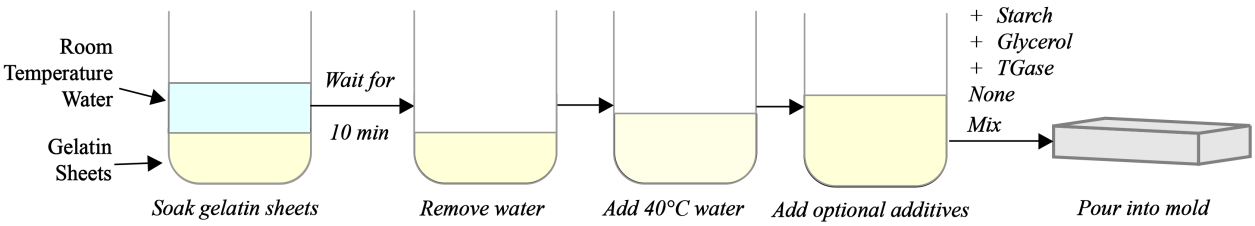

Figure 2: Workflow for preparing gelatin-based bars, including optional additions of glycerol, cornstarch, or transglutaminase (TGase) depending on the experiment. Variants used: gelatin only, gelatin–starch, gelatin–glycerol, and gelatin–glycerol–TGase [10].

3.1 Programmable Weak Point Testing

Bars were fabricated with distinct strong (gelatin–cornstarch) and weak (pure gelatin) regions. Each bar was suspended in a warm water bath and mounted to a servo motor arm to simulate repeated mechanical stress and accelerate dissolution. The servo motor was programmed to oscillate with an angular amplitude of 15° (±0.262 radians from center) at a frequency of 4 Hz, generating consistent cyclic loading on the bar.

Figure 3 illustrates the experimental setup: the gelatin bar is fixed to a mount at one end, swings back and forth across a small angle, and is partially submerged in warm water. This setup enabled standardized testing of failure behavior under combined mechanical and environmental conditions. For each trial, we recorded the time to failure, break location, and segment-specific dissolution durations.

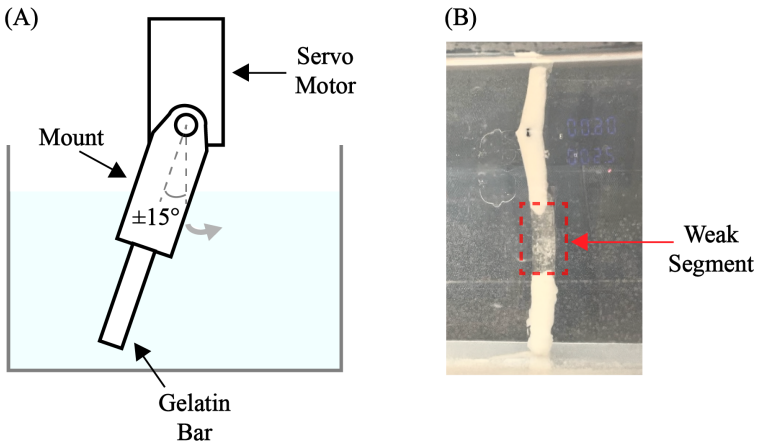

Figure 3: Servo motor test setup for weak point experiments. (A) Schematic diagram showing a gelatin bar mounted to a servo arm. (B) Photograph of the actual setup during testing, with the gelatin bar partially submerged.

3.2 Crosslinked vs. Non-Crosslinked Dissolution Comparison

Two bars were fabricated: one using a gelatin–glycerol–water mixture, and one using the same base composition with added transglutaminase (TGase) for enzymatic crosslinking[10]. Both bars were qualitatively assessed for visual and tactile properties such as transparency, elasticity, and stiffness. They were then submerged side-by-side in a warm water bath under identical conditions

to compare dissolution time.

3.3 Manual Stretch and Failure Testing

Bars were manually stretched by gripping each end and applying slow, steady tension until breakage. The total elongation before failure was measured using a ruler.

3.4 Tools and Equipment

- Custom 3D-printed molds for gelatin casting
- Standard servo motor (oscillating $\pm 15^\circ$ at 4 Hz)
- Warm water bath with temperature control
- Ruler, camera, and stopwatch for measurement and recording
- Digital scale for precise ingredient proportioning
- Gelatin sheets, cornstarch, and glycerol
- Transglutaminase (TGase): total available quantity limited to 50 mg

This setup serves as the foundation for future experiments involving programmable extrusion mechanisms. Planned implementations include modified 3D printers or syringe pumps capable of depositing weak and strong gelatin formulations dynamically, enabling regenerative soft structures[10].

4 Results

Two main experiments were conducted to evaluate gelatin-based materials for programmable breakdown: (1) investigating weak point failure based on material composition and geometry, and (2) comparing the mechanical and dissolution properties of crosslinked versus non-crosslinked gelatin bars.

These findings support the hypothesis that localized material composition and crosslinking can enable predictable breakdown and durable structural design in regenerative robots.

4.1 Programmable Weak Points and Failure Behavior

Bars were fabricated with a central "weak point" made from pure gelatin and surrounded by stronger gelatin–cornstarch segments (ratios ranging from 4:1 to 2:1). When submerged in warm water and subjected to cyclic mechanical stress via a servo motor (oscillating at 4 Hz with an angular amplitude of 15°), all bars reliably failed at the weak center.

Two key metrics were analyzed: (1) the dissolution time contrast between strong and weak segments, and (2) the time to break as a function of weak segment size, measured by the proportion of the bar composed of pure gelatin. Both showed clear trends: increasing cornstarch content in the strong segment enhanced water resistance, while larger weak segments led to faster overall failure. These results demonstrate that both material composition and geometric placement can be effectively leveraged to embed programmable weak points within a soft structure.

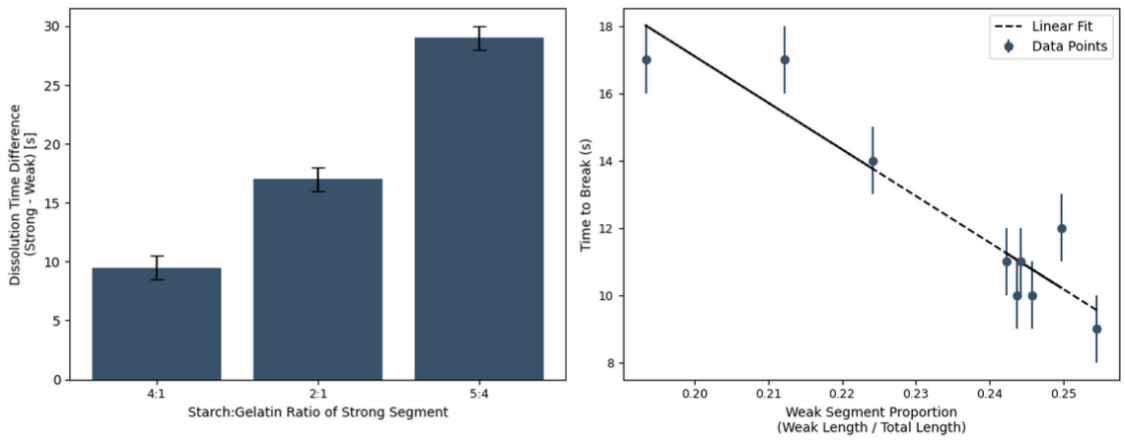

Figure 4: (Left) Dissolution time difference between strong and weak segments vs. starch-to-gelatin ratio. (Right) Weak point proportion vs. time to break.

4.2 Crosslinked vs. Non-Crosslinked Gelatin

To test durability enhancements, two bars were made: one with a gelatin–glycerol–water mixture, and one with the same mixture plus transglutaminase (TGase). Despite using only 50 mg of TGase, the crosslinked sample demonstrated superior properties[10].

Compared to the non-crosslinked bar, the TGase bar was stiffer, more resistant to stretching, and substantially more water-resistant. In warm water, the non-crosslinked bar fully dissolved in 30 s, while the TGase bar remained intact after 10 minutes. These differences were quantitatively compared using three metrics: (1) break distance measured from the right edge of the bar, (2) stretch length prior to failure, and (3) dissolution duration.

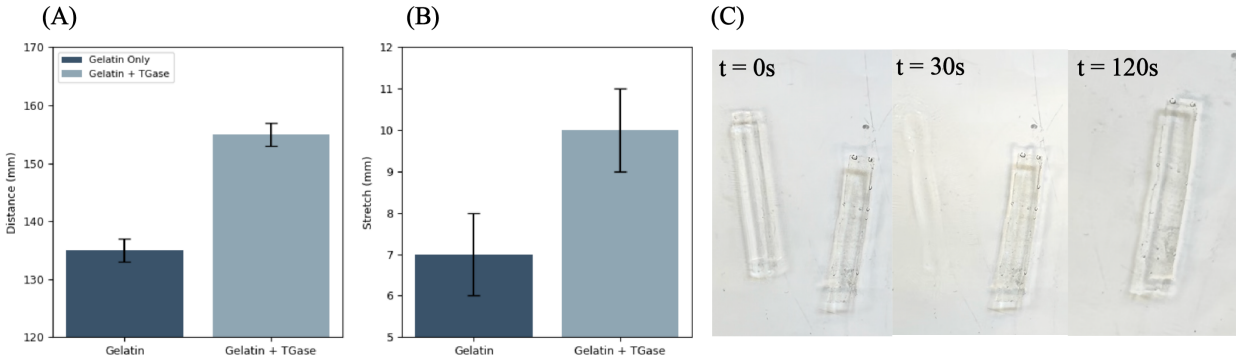

Figure 5: Comparison of non-crosslinked and TGase-crosslinked gelatin bars. (A) Break distance under manual tension. (B) Stretch length before failure. (C) Time-lapse images at 0 s, 30 s, and 120 s during dissolution in warm water, showing rapid degradation of the non-crosslinked bar. Error bars reflect estimated variability from manual measurements.

Together, these results demonstrate that (1) structural breakdown can be predictably guided using programmable weak points, and (2) enzymatic crosslinking significantly improves gelatin's strength and water resistance. These features are essential for enabling soft robots that can selectively dissolve and regrow structural components—core requirements for regenerative functionality[4].

5 Discussion & Conclusion

The experimental results provide promising early validation for the hypothesis: that localized control over material composition and crosslinking enables programmable weak points and structurally durable regions within soft robotic frameworks. Specifically, pure gelatin was shown to dissolve rapidly and fail under modest stress, while gelatin crosslinked with transglutaminase (TGase) exhibited strong resistance to both mechanical deformation and water-based degradation.

These findings directly support the project's objective of achieving programmable material removal as a mechanism for self-repair, structural reconfiguration, and morphological adaptation. The combination of selectively dissolvable "weak" regions with robust "strong" segments establishes a foundational strategy for dynamic shape control in regenerative soft robots[4].

Several limitations were encountered during the study, the most significant being the limited availability of TGase. This constraint restricted the ability to replicate experiments and limited further exploration of design parameters, including the integration of programmable weak points in crosslinked samples. Additionally, while servo motor testing provided a repeatable method for introducing mechanical stress, the role of mechanical loading in influencing breakdown remained unclear due to the overwhelming effect of water exposure.

Despite these constraints, the project establishes a basis for future work. The next milestone is the integration of a programmable material extrusion mechanism, likely through modification of a 3D printer or syringe-based system[10]. This would enable the spatially controlled deposition of both weak and strong materials to dynamically form and regenerate robot structures.

Future experiments should systematically examine the effects of varying TGase concentrations, explore alternative crosslinking agents, and evaluate the impact of additives such as plasticizers or thickeners for tuning mechanical strength and dissolution behavior. Additionally, quantitative studies should measure failure times under different types of applied forces and assess the ability to localize material breakdown through controlled mechanical inputs.

In conclusion, this work presents a scalable, low-cost strategy for constructing soft regenerative structures using accessible, biodegradable materials. While still in the exploratory stage, the demonstrated material logic lays the groundwork for future systems capable of growth, self-repair, and adaptive morphing—bringing soft robotics a step closer to the biological principles of resilience and regeneration[4].

References

[1] S. S. Kotha, N. Akter, S. H. Abhi, *et al.*, "Next generation legged robot locomotion: A review on control techniques," *Heliyon*, vol. 10, no. 18, e37237, 2024, ISSN: 2405-8440.

[2] Z. J. Patterson, W. Xiao, E. Sologuren, and D. Rus, *Safe control for soft-rigid robots with self-contact using control barrier functions*, 2024.

[3] M. Polzin, Q. Guan, and J. Hughes, "Robotic locomotion through active and passive morphological adaptation in extreme outdoor environments," *Science Robotics*, vol. 10, no. 99, eadp6419, 2025.

[4] C. Lange and M. Brand, "Vertebrate brain regeneration – a community effort of fate-restricted precursor cell types," *Current Opinion in Genetics Development*, vol. 64, pp. 101–108, 2020, Cell reprogramming, regeneration and repair, ISSN: 0959-437X.

[5] E. Kanhere, T. Calais, S. Jain, *et al.*, "Upgrading and extending the life cycle of soft robots with in situ free-form liquid three-dimensional printing," *Science Robotics*, vol. 9, no. 97, eadn4542, 2024.

[6] E. D. Dottore, A. Mondini, N. Rowe, and B. Mazzolai, "A growing soft robot with climbing plant–inspired adaptive behaviors for navigation in unstructured environments," *Science Robotics*, vol. 9, no. 86, eadi5908, 2024.

[7] H. Bai, Y. S. Kim, and R. F. Shepherd, "Autonomous self-healing optical sensors for damage intelligent soft-bodied systems," *Science Advances*, vol. 8, no. 49, eabq2104, 2022.

[8] **Chao Liu**, Q. Lin, H. Kim, and M. Yim, "Smores-ep, a modular robot with parallel self-assembly," *Autonomous Robots*, 2022, ISSN: 1573-7527.

[9] D. Hardman, J. Hughes, T. G. Thuruthel, K. Gilday, and F. Iida, "3d printable sensorized soft gelatin hydrogel for multi-material soft structures," *IEEE Robotics and Automation Letters*, vol. 6, no. 3, pp. 5269–5275, 2021.

[10] D. Hardman, T. George Thuruthel, and F. Iida, "Self-healing ionic gelatin/glycerol hydrogels for strain sensing applications," eng, *NPG Asia materials*, vol. 14, no. 1, 2022, ISSN: 1884-4049.

[11] J. Tacx, H. Schoffeleers, A. Brands, and L. Teuwen, "Dissolution behavior and solution properties of polyvinylalcohol as determined by viscometry and light scattering in dmso, ethyleneglycol and water," *Polymer*, vol. 41, no. 3, pp. 947–957, 2000, ISSN: 0032-3861.