

Figure 8.18: Gradual evolution of tridimensional cranial remodeling over time using the C1 and C3 devices.

For skin expanders, axial or frontal expansion was measured as the distance between the base of the device and the extent of the silicone membrane expansion (Figure 8.19). While distraction time and expansion magnitude correlated for most devices, notable deviations were observed for SE1 and SE2.

The SE2 mechanism expanded nearly instantaneously at the start, reaching 6 mm within the first five minutes. This rapid expansion was attributed to the higher rigidity of the inner section of the conical spring, coupled with increased layer density in this region due to FFF process. Subsequent anchor failures produced a stepped expansion pattern. In contrast, the outer spring regions stored less energy and, remaining anchored longer, experienced stress relaxation, reducing stiffness and energy release over time. For SE1, the larger, solid degradable frame delayed expansion due to prolonged degradation of the upper and lower PVA layers. As shown in Figure 8.21, residual PVA was still present at the conical spring tip at the end of the test (402 minutes), contributing to a greater final expansion.

The SE3 device employed a degradable spring mechanism like C3 and C5 mechanisms, initially compressed and gradually releasing stored energy. Expansion began exponentially after 10 minutes, with shorter intervals between expansions until the equilibrium was reached. In contrast, the wicker-based mechanism (SE4) lacked sufficient stored energy to expand the silicone membrane. The structure remained compressed until water-induced material relaxation occurred at 17 minutes, after which the mechanism was compressed further by the membrane, resulting in negative expansion. When tested without artificial skin, SE4 demonstrated an exponential shape-change pattern (Figure 8.20), returning to its as-printed dome shape as PVA degradation released the stored energy.

Images of the performance of SE1, SE2, SE3, and SE4 with and without artificial skin are shown in Figure 8.21, Figure 8.22, Figure 8.23, Figure 8.24 and Figure 8.25 respectively.

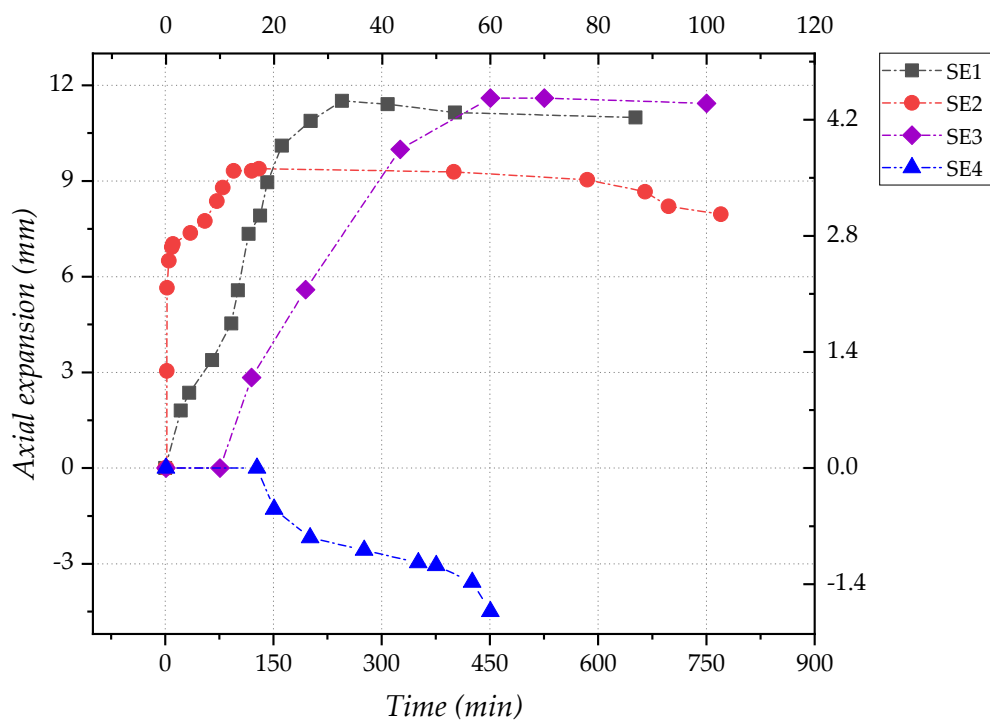


Figure 8.19: Comparison of skin expansion achieved by different shape-morphing expanders. The auxiliary axes represent the time-dependent evolution of skin expansion for SE3 and SE4.

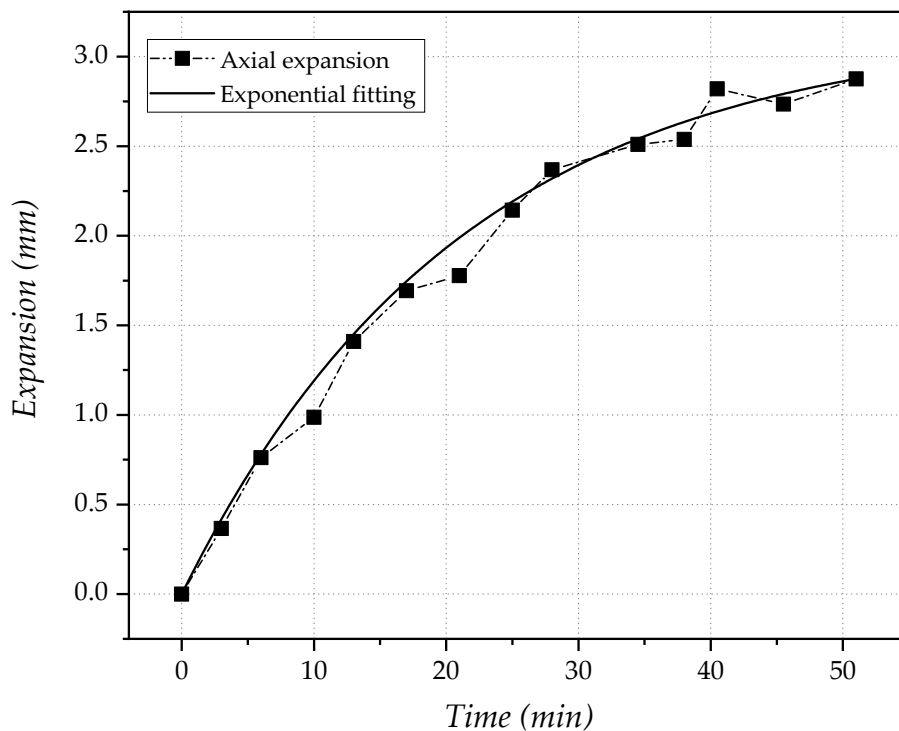


Figure 8.20: Expansion evolution of the SE4 skin expander tested without the artificial skin.

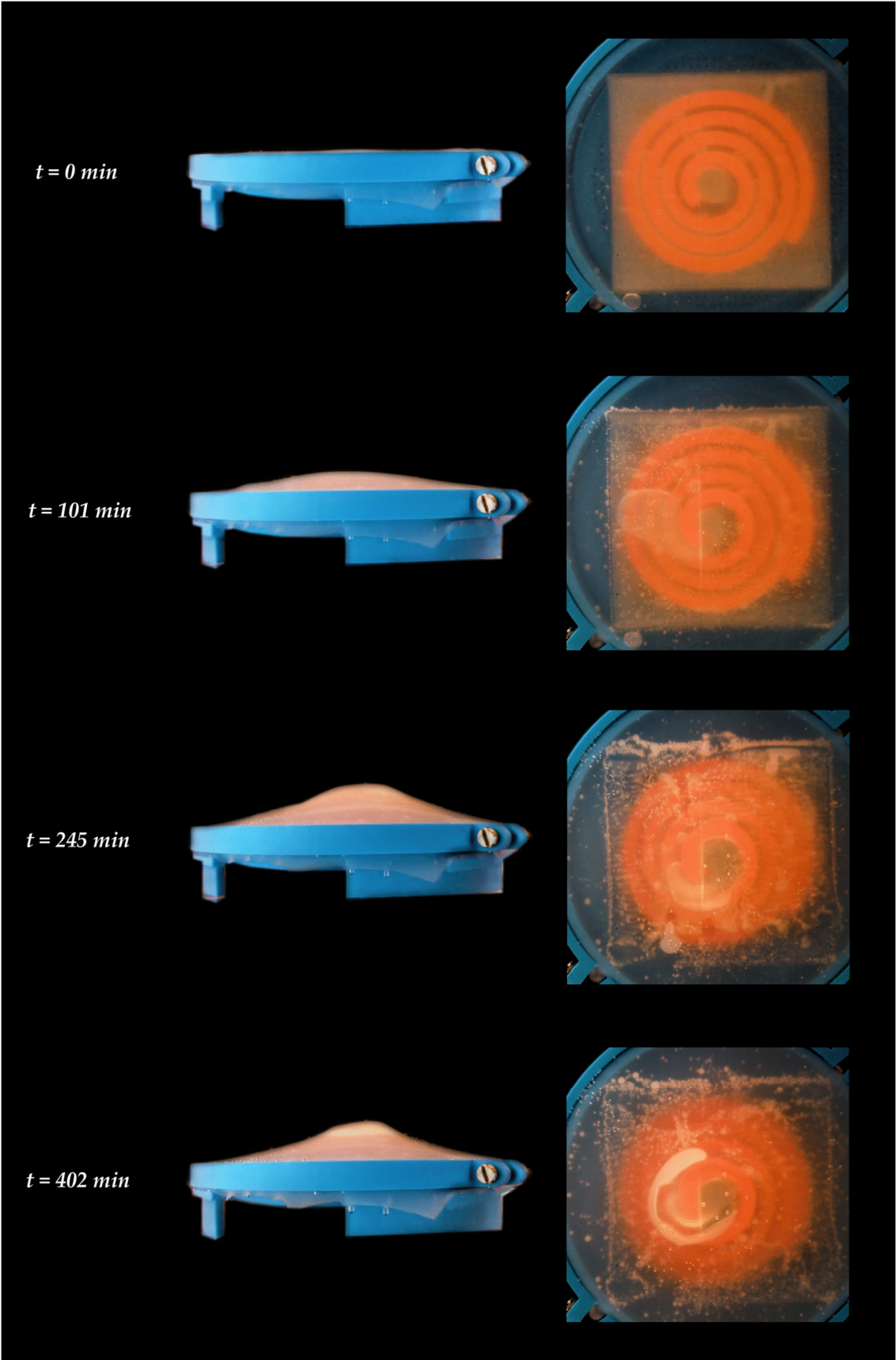


Figure 8.21: Evolution of degradation over time of the shape-morphing skin expander SE1.

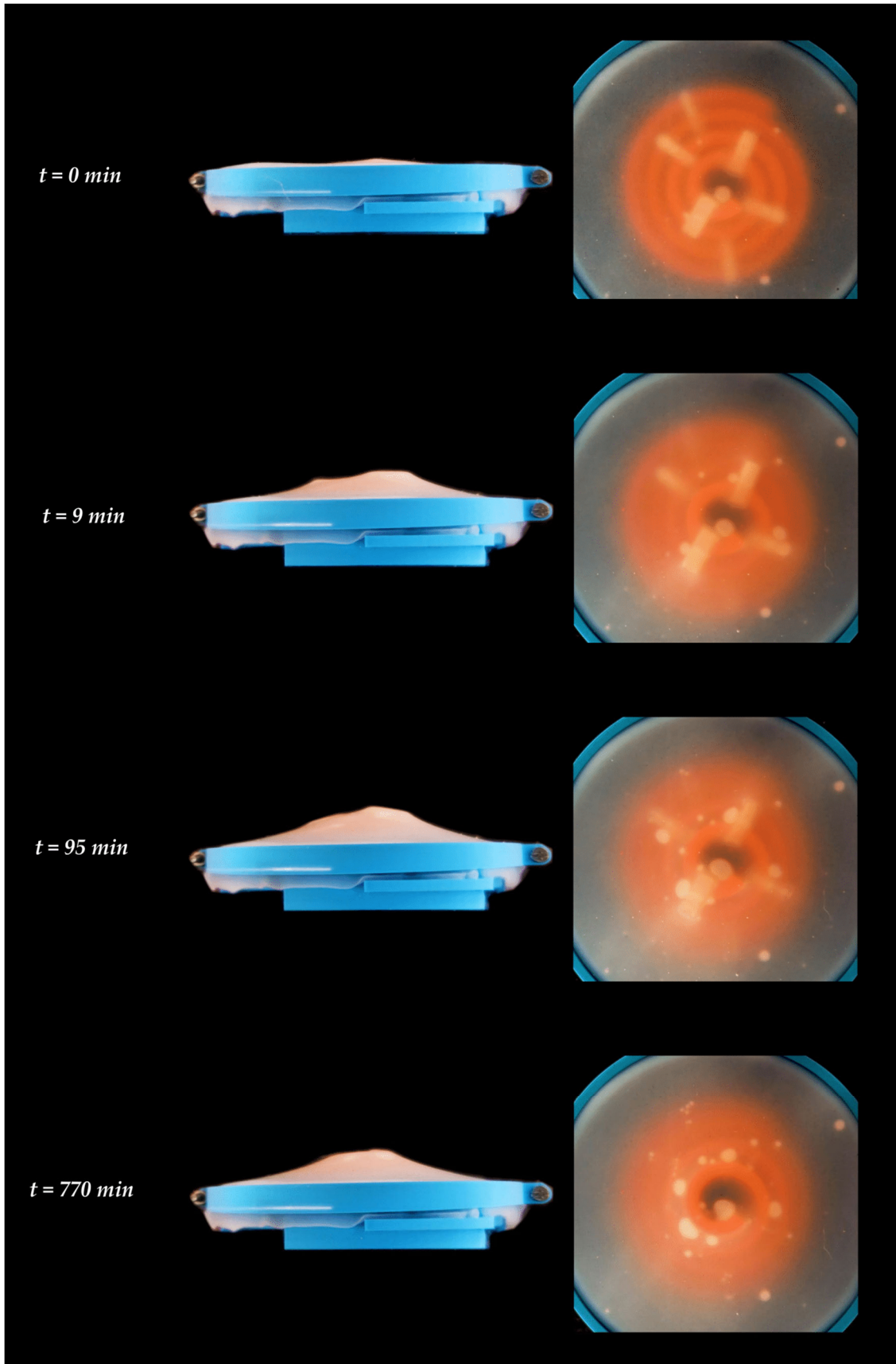


Figure 8.22: Evolution of degradation over time of the shape-morphing skin expander SE2.

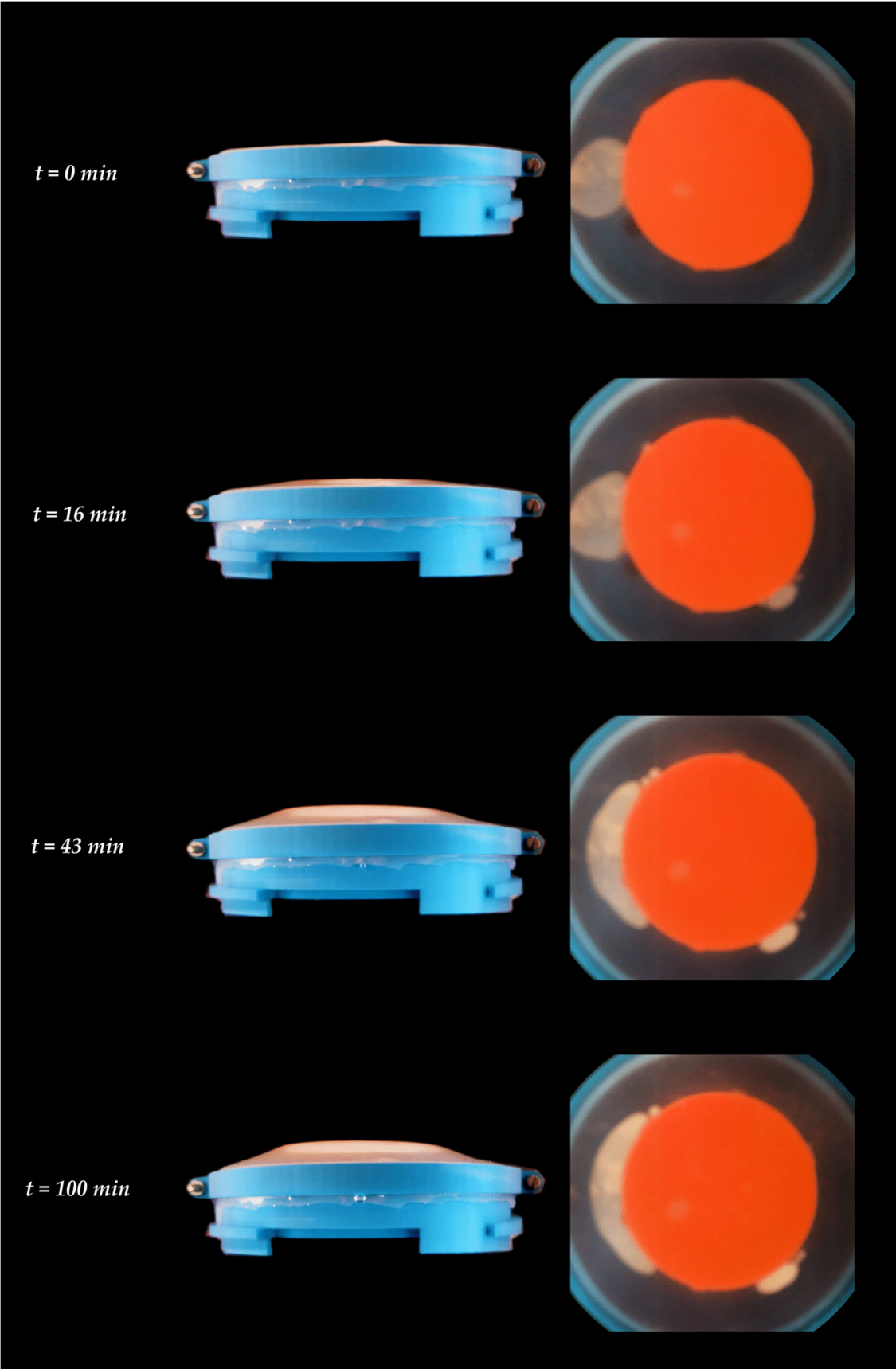


Figure 8.23: Evolution of degradation over time of the shape-morphing skin expander SE3.

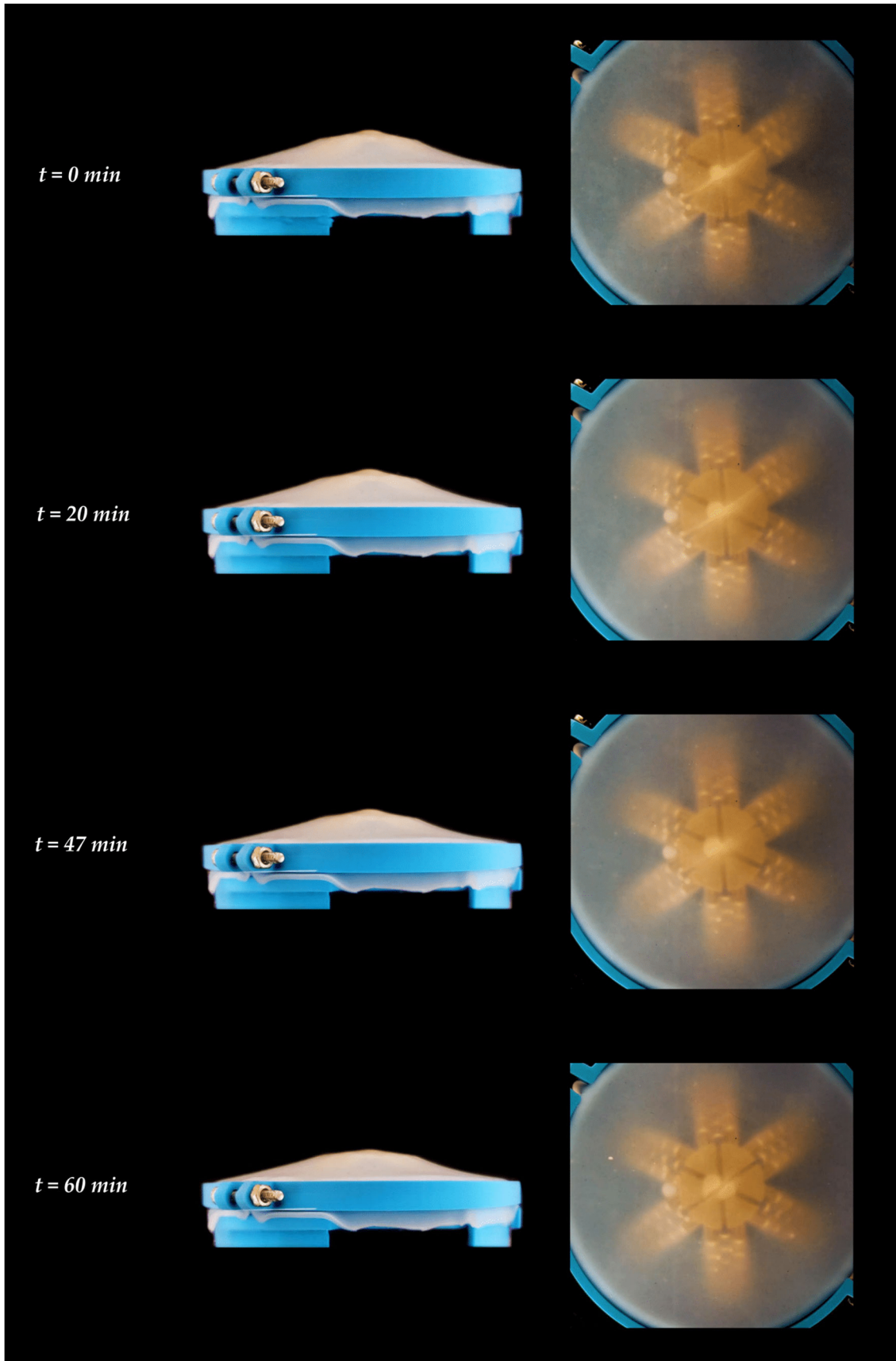


Figure 8.24: Evolution of degradation over time of the shape-morphing skin expander SE4.

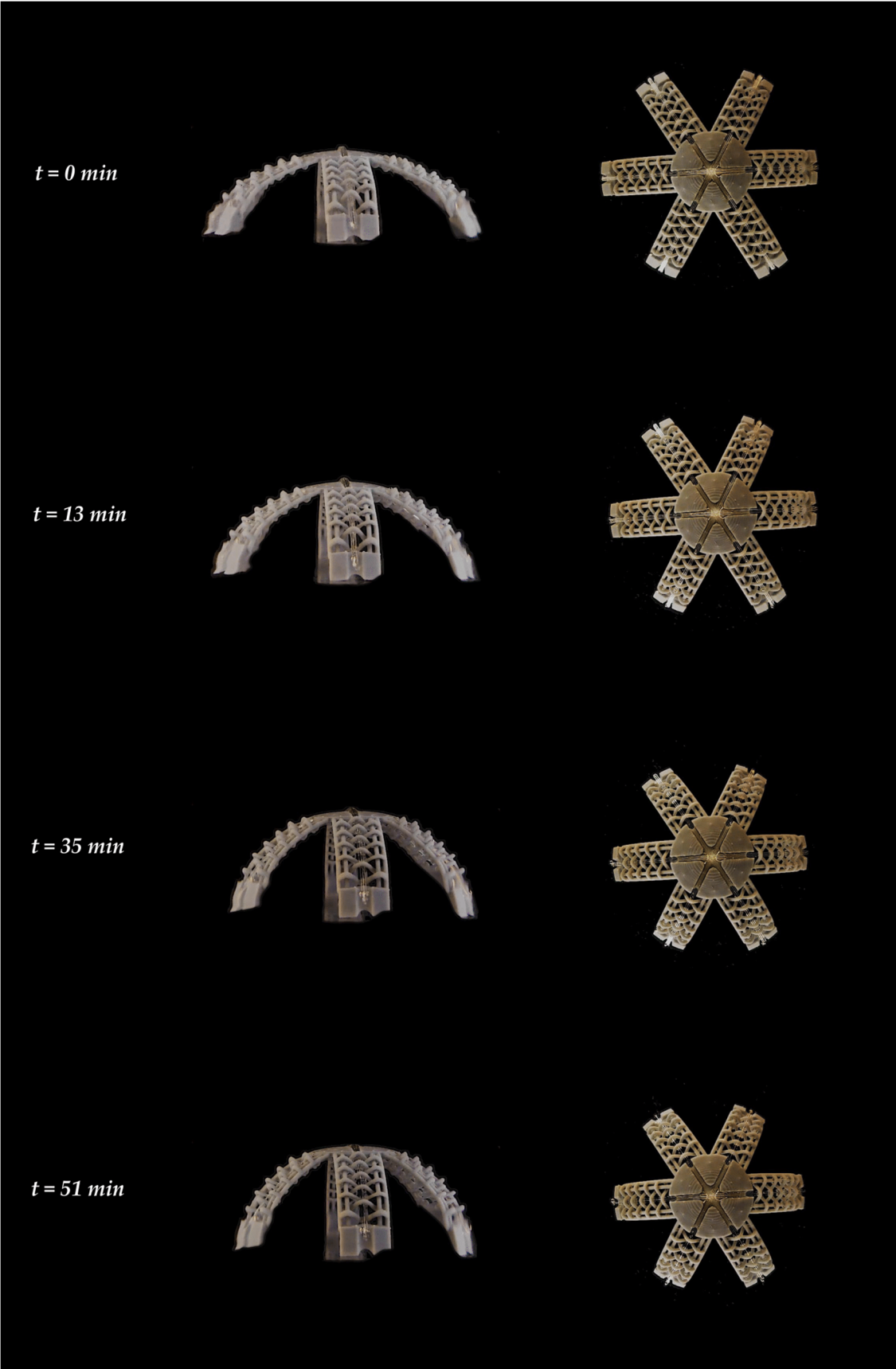


Figure 8.25: Evolution of degradation over time of the SE4 skin expander tested without the artificial skin.

8.4. Discussion

The use of spring-based devices in craniosynostosis treatment represents a highly innovative approach. Among the different configurations evaluated, the omega-shaped spring, modeled from commercially available devices, has proven to be the most effective in achieving significant distraction. Its superiority lies in its greater ability to store elastic energy during the loading process, enabling higher efficiency and sustained shape transformation over time (Figure 8.5). However, incorporating a degradable serpentine spring as an anchoring element, similar to the design of device C5, offers a controlled and progressive release of the omega-shaped device. This combination integrates the advantages of spring-based craniosynostosis treatments and traditional bone distractors while supporting a less invasive surgical procedure compared to conventional distractor systems [10,72,73,78,107,108]. Additionally, by modifying the thickness and geometry of the anchors, the distraction force applied to the sutures can be fine-tuned to optimize bone remodeling.

The effectiveness of expansion devices is directly related to their ability to store elastic energy. It has been observed that implants that accumulate greater elastic energy produce more prolonged distraction over time (Figure 8.5, Figure 8.11 and Figure 8.19). The strategy of assembling a degradable rigid element with an elastic component provides gradual distraction, which could be beneficial in treating various clinical cases. In this context, stress relaxation behavior varies depending on the material used. Wicker-based structure manufactured with photopolymerizable resin exhibit significantly more pronounced stress relaxation compared to those made of PETG. This factor is crucial in device design, as excessive stress relaxation can reduce expansion efficiency.

Furthermore, the use of (bio)degradable materials for the flexible component can also be explored, ensuring that degradation occurs only after the rapidly degrading anchors have dissolved. This strategy would eliminate the need for a second surgery to remove the spring or expander once the treatment is completed.

Optimizing both the springs and their anchoring mechanisms is crucial for achieving the necessary mechanical response in infant cranial remodeling. As demonstrated with the combination of C1 and C3 in the metopic and coronal sutures, implanting different devices along various sutures is feasible, allowing the treatment to be tailored to syndromic craniosynostosis cases (Figure 8.18). However, the performance of these devices should first be validated through animal models or finite element simulations before transitioning to human trials.

For applications requiring higher distraction forces, torsion springs with one or two coils could be used [99]. Among the analyzed shape-morphing skin expanders, the conical spring design presented some drawbacks, particularly in the uneven force distribution caused by internal

gaps in the structure, which could lead to localized tissue stresses. In contrast, the auxetic model provides a more uniform force distribution, reducing the risk of complications. However, its unidirectional expansion limits its applicability.

On the other hand, the wicker-based device offers a more organic expansion shape and, when fabricated with metals such as superelastic nitinol, could achieve the desired mechanical performance. The optimization of this design should focus on ensuring that the degradable bars embedded within the woven structure initially maintain the device in a flat position and allow for progressive volumetric expansion. However, a limitation of this approach is its non-telescopic nature, which requires a large initial implantation area that decreases as the device expands (Figure 8.25, top view).

From a surgical perspective, the expansion process should begin approximately three weeks post-surgery to allow for proper wound healing [137]. This delay can be achieved by adjusting the rigidity of the degradable element, as demonstrated with SE3 (Figure 8.19). Additionally, coatings can be applied to slow down degradation, ensuring a more homogeneous process and preventing localized corrosion. Localized degradation could lead to catastrophic anchor failure, resulting in abrupt shape changes and the sudden release of stored elastic energy, an undesirable effect that could damage surrounding tissues.

In addition, the surgeon must ensure that the treatment aligns with suture remodeling [72,73,94] and the mechanical and biological creep properties of the skin during the expansion process to prevent patient discomfort [112,118,124]. Achieving this balance requires careful selection of materials that provide both structural integrity and controlled expansion. Shape-morphing medical devices, therefore, must be produced from biocompatible and biodegradable metals or metal-reinforced polymers to ensure adequate stiffness within a compact volume. This characteristic is not only essential for effective skin expansion but also plays a crucial role in craniosynostosis treatment, where cranial distraction indirectly contributes to the expansion of the overlying skin.

The use of these materials also helps mitigate the stress relaxation observed in experimental tests, improving device reliability over time. In this regard, additive manufacturing is a suitable approach for producing these devices, as it allows them to conform to the curvature of the skull, ensuring that the spring force vector remains perpendicular to the suture, minimizing the risk of improper remodeling.

Moreover, multi-material solutions can be explored to perfectly integrate active and degradable elements, removing the need for component assembly. However, conventional manufacturing methods should not be overlooked. Preformed shapes, as used in current surgical procedures [100,105], may offer advantages, particularly for biodegradable materials, which tend to degrade more uniformly when produced through traditional processes compared to additive manufacturing.

Mechanical and degradation tests are essential for developing a comprehensive guide for surgeons, enabling the selection of appropriate spring-based medical devices and degradable anchoring elements to regulate the force exerted and its temporal distribution throughout the shape-morphing implant's lifespan.

As outlined in Chapter 7, there are alternative shape-shifting design strategies that should be explored, such as devices based on plastic deformation of degradable elements or multi-step anchors that progressively erode to release active components. These strategies may offer innovative solutions for both craniosynostosis and skin expansion applications, further advancing the field of minimally invasive, shape-morphing medical devices. Potential applications include bioresorbable implants for controlled drug delivery, resorbable scaffolds for tendon and ligament repair, dynamic orthopedic implants for pediatric deformities, and bioresorbable scaffolds for regenerative medicine. Furthermore, these approaches can be adapted to a variety of degradable materials, including ceramics, metals, and composites, allowing for tailored degradation rates and mechanical properties to suit specific clinical needs.

8.5. Conclusions and future proposals

The development of shape-morphing medical devices triggered by (bio)degradation shows great potential for the treatment of craniosynostosis and skin expansion. By integrating active/flexible and degradable components, these implants enable controlled and progressive distraction/expansion, addressing key challenges such as re-synostosis and uneven force distribution.

Among the tested designs, omega-shaped springs achieved the highest distraction forces, while serpentine spring demonstrated potential as degradable softening anchors. In skin expanders, auxetic structure provided uniform force distribution but was unidirectional, whereas wicker-based mechanism allowed for more organic volumetric expansion. The optimization of anchoring mechanisms is essential for controlling energy release and ensuring proper device performance. Likewise, improving the active element is also crucial, as it must be capable of storing the maximum amount of energy without undergoing permanent deformation, which could prevent the implant from returning to its original shape and compromise its functionality.

To further enhance these technologies, future efforts should focus on multiple aspects. In craniosynostosis treatment, the development of multi-suture devices is necessary to optimize interaction between perpendicular distraction axes, allowing for the treatment of more complex cranial conditions. Regarding degradable anchors, further refinement of materials and coatings is needed to slow degradation while preventing localized failure. Additionally, advancements in multi-material additive manufacturing would enable seamless integration of

active and degradable parts, enhancing reliability and reducing assembly complexity. Alternative shape-morphing design strategies, such as plastically deformable elements or multi-step anchors, should also be explored to expand clinical applications and improve control over degradation rates.

For skin expansion, achieving uniform force distribution remains a critical goal. Future refinements may focus on developing multidirectional auxetic springs and improving manufacturing techniques for wicker-based designs. Establishing standardized mechanical and degradation testing protocols will also be crucial in guiding clinicians to select the most suitable devices based on patient-specific needs.

To translate these innovations into clinical practice, preclinical animal studies should be prioritized to validate safety and efficacy, paving the way for clinical trials that assess long-term patient outcomes. Additionally, integrating these devices into surgical workflows will require adapting implantation techniques and postoperative care to fully leverage their minimally invasive nature. With continued research, validation, and clinical application, these shape-morphing technologies hold a significant promise in advancing broader biomedical applications.

9. Conclusions and future research proposals

9.1. Main conclusions

Throughout this PhD thesis, the proposed objectives have been achieved and the foundations for significant progress in the emerging field of 4D printing have been established, particularly regarding the incorporation of degradation as a triggering stimulus in smart systems and structures capable of shape shift.

Below, the main conclusions derived from this PhD thesis are summarized:

1. *Development and validation of universal ontology for 4D printed material systems and structures.* Versatile and ambitious ontology has been designed and validated, along with an innovative coding scheme that systematically and comprehensively describes the lifecycle of 4D printed actuators and devices. This tool integrates fundamental aspects such as initial geometry, shape-morphing principles, triggering stimuli, intermediate and final shapes, and the materials and additive manufacturing technologies employed. It has been successfully applied to a set of 54 representative examples. Furthermore, integrating this ontology with generative artificial intelligence algorithms has demonstrated exceptional potential to foster creativity and innovation in the design of shape-shifting structures.
2. *Innovation in the use of (bio)degradable materials and rapid prototyping to create actuators that change shape through degradation.* Experimental studies have proven the suitability of combining polymers such as PVA and PETG, processed using Fused Filament Fabrication (FFF), to produce multimaterial 4D actuators. It has been demonstrated that PVA acts as a temporary “lock”, degrading in aqueous conditions and gradually releasing stored energy, while PETG contributes elasticity and energy storage capacity, maintaining its mechanical properties despite certain plasticizing effects. This synergy enables the creation of actuators with controlled, programmable, and intelligent metamorphoses.
3. *Creation and classification of the most comprehensive collection of actuators that change shape due to the degradation of one of their components.* The largest available collection of degradation-activated shape-morphing actuators has been developed, with 50 mechanisms designed, manufactured, and tested. These actuators have been classified into four main families according to the structural configuration of the degradable elements: external frames, interlocking elements, plastically deformed regions, and

progressively degradable anchors. Experiments have shown shape recoveries of nearly 80% in polymer systems, and the strategy has been successfully transferred to metal prototypes based on Laser Powder Bed Fusion (LPBF).

4. *DfAM strategy and transferability to various technologies and materials.* The implementation of a Design for Additive Manufacturing (DfAM) strategy has allowed the successful translation of actuators developed via rapid prototyping techniques to high-performance additive manufacturing processes, such as LPBF. This approach facilitates the production of multimetallic actuators with shape-changing capabilities and demonstrates that proof-of-concept results obtained with polymer systems can be extended to other functional materials, thus broadening the potential applications of this technology.
5. *Creation of proof-of-concept shape-morphing implants for the treatment of craniosynostosis and skin expansion.* Degradation-activated actuators have been successfully applied in the design and prototyping of conceptual medical devices aimed at addressing critical challenges in biomedical engineering. In the treatment of craniosynostosis, distraction osteogenesis implants have been developed employing innovative mechanisms such as omega-shaped and serpentine springs. These devices are designed to exert a constant and controlled force on cranial sutures over time, promoting bone remodeling. Similarly, in skin expansion, conical springs, auxetic designs and organic structures inspired by wicker patterns have been explored to enable progressive, uniform, and adaptive expansion. These proofs-of-concept not only validate the technical feasibility of integrating biodegradable actuators into smart implants but also open new possibilities for developing minimally invasive and personalized interventions with the potential to significantly improve clinical outcomes and patients' quality of life.
6. *Contribution to the scientific community and dissemination of knowledge.* This PhD thesis systematized the field of 4D printing through two key tools: the creation of an ontology for coding 4D printed material systems and structures, and the development of a library of degradation-activated actuators designed in accordance with FAIR (Findability, Accessibility, Interoperability, and Reusability) principles. These resources are available to all interested parties, enabling access to the original files, replication of experiments, or modifications for new projects. Additionally, the standardization of geometries, shape-morphing principles, triggering stimuli, materials, and additive manufacturing technologies has created a universal language for coding 4D printed devices. The dissemination of these advances and their integration with generative artificial intelligence tools not only promotes creativity but also contributes significantly to the advancement of the field.

Overall, this PhD thesis has not only achieved its initial objectives but also opened new research lines and application in single- and multi-material additive manufacturing using (bio)degradable materials. The incorporation of a universal ontology and an innovative coding scheme has enabled the systematization and classification of the complex world of 4D actuators, while also facilitating their integration with artificial intelligence algorithms to boost design creativity. Experimental validation using degradable polymers, coupled with the successful transfer of rapid prototyping strategies to high-performance metallic systems, underscores the versatility and potential of the developed solutions. Moreover, the application of these advances in medical device design paves the way for innovative treatments for craniosynostosis and skin expansion, holding significant implications for biomedical engineering.

The integration of degradable materials within the framework of additive manufacturing has emerged as a pivotal avenue for the exploration of sustainable solutions, offering benefits across a range of disciplines. In the medical field, these advances have led to the development of smart implantable devices that facilitate tissue regeneration, reduce postoperative complications, and enable personalized treatments, as evidenced by shape-morphing implants for craniosynostosis and skin expansion. In the field of engineering, the integration of these materials and processes has the potential to contribute to the development of adaptive structural systems and high-precision components applicable in sectors as varied as automotive, aerospace, and construction, where efficient and sustainable solutions are in demand.

Furthermore, these innovations have the potential to positively impact areas such as robotics, electronics, and product design, offering new opportunities to create smart, customizable and degradable systems that respond to dynamic market needs. Consequently, the outcomes of this study offer a broad spectrum of possibilities for the enhancement of processes and the exploration of innovative applications across multiple industrial and technological domains.

9.2. Future proposals

Below are several future research directions derived from this thesis. These proposals aim to expand and consolidate knowledge in the field of shape-morphing material systems and structures through the use of degradable materials. Spanning from tissue engineering to the adaptation of shape-morphing mechanisms in metallic materials, these research directions contribute to applications in engineering, regenerative medicine, and emerging technologies.

1) Characterization of 3D printed PVA erosion as a function of stress state

During the development of this PhD thesis, the degradation of 3D printed PVA was characterized, revealing that in 100% solid samples the degradation process is similar

regardless of the infill pattern, and that the degradation rate is strongly influenced by the exposed surface-to-volume ratio. Based on these results, it is proposed to evaluate whether the energy absorbed in the PVA, resulting from its interaction with PETG during actuator training, significantly affects the erosion rate, and to determine how the tensile state influences the degradation behavior.

To investigate this, a potential experiment could involve the degradation analysis of PVA serpentine springs. The influence of stress could be examined by comparing two conditions: one spring deformed by a frame during degradation and another printed directly with the deformed shape obtained from finite element simulations (Figure 9.1). This approach would allow evaluating whether highly deformed regions exhibit accelerated degradation, as preliminary results suggest.

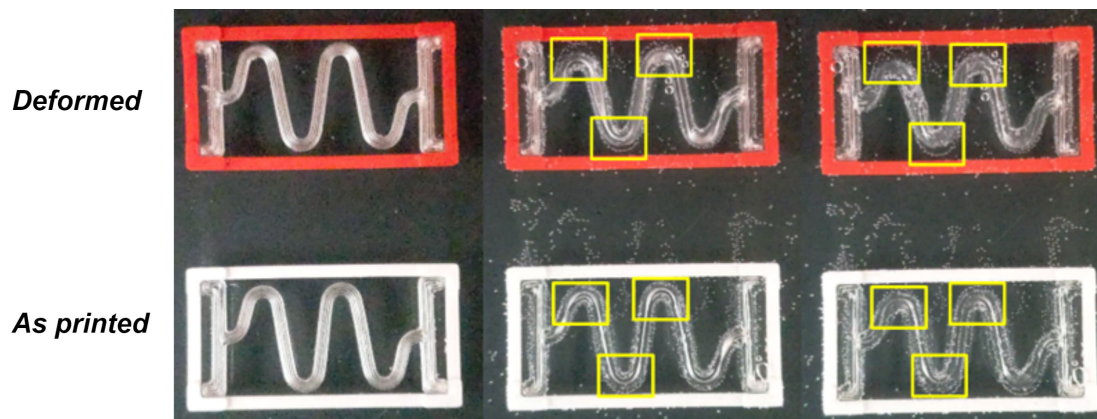


Figure 9.1: Degradation analysis of PVA serpentine springs samples. Comparison between stress-induced deformed (red frame) and directly printed springs (white frame).

2) Extension of shape-morphing mechanisms to metallic systems and structures

It is recommended that the experimental validation of the polymeric devices developed in the 4D printed actuator library be extended by redesigning them to be produced with metals (Figure 9.2). In particular, biodegradable and biocompatible alloys facilitates the actuators' development that have the potential to evolve into shape-morphing medical devices capable of adapting in harmony with patient's needs, as evidenced in Chapter 8. This study will investigate whether the design strategies applied to polymeric systems can be replicated in metallic materials or if new, specific approaches are required. This assessment will determine the applicability of current techniques and, if necessary, initiate new research avenues for the creation of adaptive structures in high-demand materials. This, in turn, will enhance their use in medical applications and other high-complexity fields.

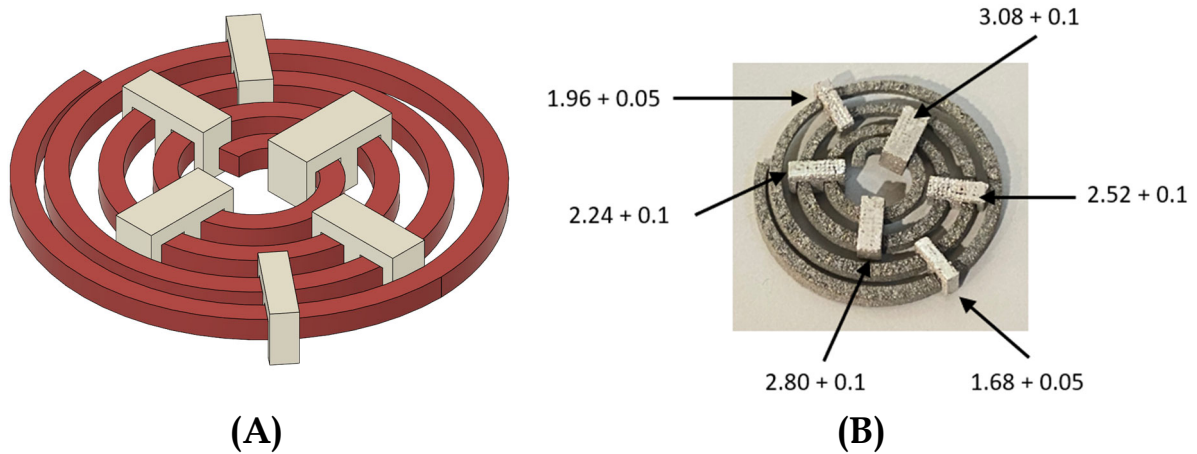


Figure 9.2: (A) Comparison between actuator 13 from the actuators library and (B) its additively manufactured version printed via LPBF with a superelastic nitinol active component and degradable WE43meo anchors. Pictures courtesy of IMDEA Materials Institute and Meotec GmbH.

3) Finite element modeling of 4D polymeric actuators activated by degradation

Currently, numerical models based on finite element analysis are being developed to integrate the behavior of polymeric actuators whose shape transformation is triggered by degradation processes (Figure 9.3). This study is being carried out in collaboration with Drs. Conall Quinn and Ted Vaughan of National University of Galway, who are also part of the consortium of the European BIOMET4D project. The implementation of a model simulating the degradation of the constituent materials is underway, enabling assessment of progressive release of energy stored in the elastic structure. This approach optimizes both flexible and degradable properties, facilitating the achievement of predefined shape transformations in a precise and reproducible manner.

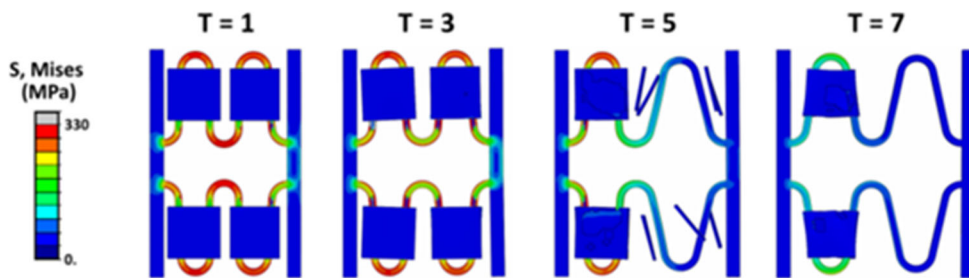


Figure 9.3: Finite element simulation of a degradable shape-shifting mechanism considering the degradation of its anchoring elements. Image courtesy of Dr. Conall Quinn.

4) Development of skin expanders based on woven structures

The proposal entails the development of skin expanders that employ woven structures to transition from a two-dimensional configuration to a three-dimensional one. This transformation facilitates the storage and release of energy, thereby facilitating the expansion of both the epidermis and dermis. This project is being conducted in collaboration with M. Eng. Carlos Aguilar, M.Sc. Oscar Contreras, and Profs. Andrés Díaz Lantada and Jon Molina,

a collection of skin expanders printed in superelastic nitinol is being developed (Figure 9.4), with a focus on designing anchors that enable controlled training of shape transformation and ensure uniform and progressive expansion of the skin tissue.

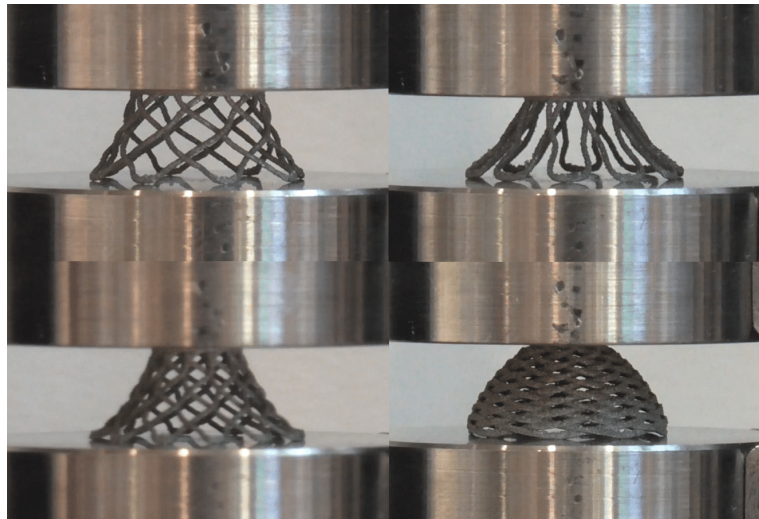


Figure 9.4: Nitinol-based woven structures for progressive tissue expansion. Picture courtesy of M. Eng. Carlos Aguilar Vega.

5) Integration of combined triggering stimuli for the creation of ultra shape-morphing actuators

The hypothesis to be investigated is that of strategies integrating the simultaneous or sequential application of various triggering stimuli, including heat, magnetism, light, pH, amongst others, in conjunction with the degradation process, with a view to inducing both immediate and progressive shape changes in multimaterial flexible structures. In scenarios involving simultaneous stimulation, the combined response of the structure will be analyzed to achieve complex transformations in a single step, whereas sequential application will allow for a controlled progression of shape transformation, generating intermediate stages that facilitate smooth and adaptive transitions.

Additionally, the exploration of the shape memory properties of PETG to recover or modify previous configurations is proposed, thereby enhancing the capacity of the polymeric systems developed in this PhD thesis to respond to multiple external signals. The theoretical modelling and experimental validation of these advanced strategies could lead to multifunctional and adaptive devices with applications in soft robotics, medical devices, and industrial automation systems.

6) Development of programmed degradable scaffolds for tissue engineering

The proposal entails the conceptualization of smart scaffolds, which are to be manufactured from biodegradable materials characterized by variable degradation rates. This approach is based on the voxel matter strategy, in which each voxel is assigned to a distinct material. In this manner, upon exposure to a degrading environment, the mechanical and biochemical

properties of the scaffold will evolve in a controlled fashion, thus promoting the colonization and migration of various cell types. The methodology to be employed involves the implementation of a three-dimensional cellular automaton to generate the initial scaffold geometry, in conjunction with an additional automaton to simulate the differential degradation of each material and the dynamics of cell colonization. This approach will facilitate the prediction of the scaffold's temporal behavior under physiological conditions.

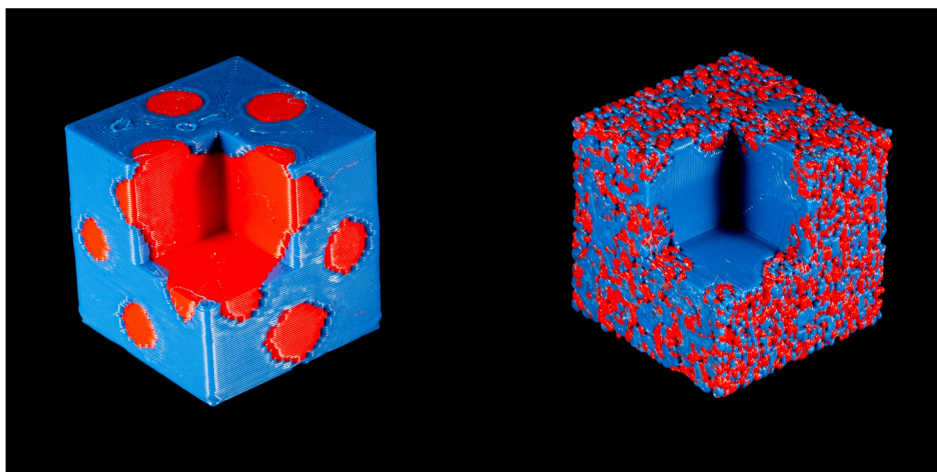


Figure 9.5: Multimaterial voxel-based scaffold generated via cellular automaton. Red represents material that degrades rapidly and blue represents material that degrades slowly. Picture courtesy of Álvaro Troyano and BEng. Isaac Castillo.

7) Validation of materials and shape-morphing implants in biological and clinical environments

A research line is proposed aimed at the comprehensive validation of the developed materials and mechanisms, beginning with studies in animal models to assess biocompatibility, the efficacy in inducing shape changes, and integration with tissue regeneration processes. Subsequently, clinical trials in human subjects will be considered to adjust and optimize the devices based on the biological response and to ensure the safety and effectiveness of the medical applications. This phased approach will enable a safe and controlled transition from the laboratory to real therapeutic applications, thereby consolidating the viability of these systems in clinical environments and enhancing their potential impact.

9.3. Summary of scientific-technological contributions

Articles in scientific journals and patents

1. Patent under analysis. Molina Aldareguia, J. M., Llorca Martínez, F. J., Patterson, J., Díaz Lantada, A., **Solórzano Requejo, W. G.**, Kopp, A., Pöstges, S. Structure comprising a first, rapidly degradable part and a second, slowly or non-degradable part. This patent has been developed in collaboration with IMDEA Materials Institute, Meotec GmbH, and Universidad Politécnica de Madrid as part of a joint research effort on biodegradable structures with programmed activation.

2. **Solórzano-Requejo, W.**, Vega, C. A., Martínez, R. Z., Bodaghi, M., & Lantada, A. D. (2025). Ontology for smart 4D printed material systems and structures synergically applied with generative artificial intelligence for creativity promotion. *Smart Materials and Structures*, 34(1), 015045. <https://doi.org/10.1088/1361-665X/ad9dca>
3. **Solórzano-Requejo, W.**, Martínez Cendrero, A., Altun, A. A., Nohut, S., Ojeda, C., García Molleja, J., Molina-Aldareguia, J., Schwentenwein, M., & Díaz Lantada, A. (2024). Topology optimisation and lithography-based ceramic manufacturing of short-stem hip prostheses with enhanced biomechanical and mechanobiological performance. *Virtual and Physical Prototyping*, 19(1), e2387280. <https://doi.org/10.1080/17452759.2024.2387280>
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7. **Solórzano Requejo, W.**, Ahijón, B. L., Corchado, C., Llorca, J., Lantada, A. D., Patterson, J., & Díaz-Payno, P. J. (2024). An ECM scaffold combined with a compliant 3D printed spring-shaped reinforcement for cartilage engineering applications. <https://doi.org/10.1101/2024.01.31.575642>
8. Martínez Cendrero, A., Franco Martínez, F., **Solórzano Requejo, W. G.**, & Díaz Lantada, A. (2022). Open-source library of tissue engineering scaffolds. *Materials & Design*, 223, 111154. <https://doi.org/10.1016/j.matdes.2022.111154>
9. **Solórzano-Requejo, W.**, Ojeda, C., & Díaz Lantada, A. (2022). Innovative Design methodology for patient-specific short femoral stems. *Materials*, 15(2), Article 2. <https://doi.org/10.3390/ma15020442>

Publications in proceedings from scientific conferences and participation in congresses

10. López-Arrabal, A., Guzmán-Bautista, Á., **Solórzano-Requejo, W.**, Sancho-Arellano, A., Franco-Martínez, F., & Lantada, A. D. (2025). Path Planning Design for Robot Based Non-Planar Additive Manufacturing Case Study: Coronary Stent. *2025 9th International Conference on Mechanical Engineering and Robotics Research (ICMERR)*, 17–21. <https://doi.org/10.1109/ICMERR64601.2025.10949923>

11. **Solórzano-Requejo, W.**, Quinn, C., Martínez, V., Molina-Aldareguia, J., Vaughan, T., Díaz Lantada, A. & Patterson, J. (2024). Finite element modelling aided design of shape morphing implants triggered by biodegradation: *18th International Conference on Biomedical Engineering (Singapur)*
12. **Solórzano-Requejo, W.**, Franco Martínez, F. & Díaz Lantada, A. (2024). Artificial intelligence empowered design of shape morphing polymeric actuators triggered by biodegradation: *4D Materials Design and Additive Manufacturing Conference 2024 (Corsica, France)*
13. **Solórzano-Requejo, W.**, Aguilar, C., Callejo, G., & Díaz Lantada, A. (2024). Biodegradable biodevices: a design approach based on cellular automaton: *Proceedings of the 17th International Joint Conference on Biomedical Engineering Systems and Technologies*, 34–41. <https://doi.org/10.5220/0012313600003657>
14. Lantada, A., Vega, C., Martínez, R., Rendón, M., Li, M., Contreras-Almengor, Ó., Ordoño, J., **Solórzano-Requejo, W.**, Vasic, M., Munoz-Guijosa, J., & Molina-Aldareguia, J. (2024). Additive manufacturing of nitinol for smart personalized medical devices: current capabilities and challenges: *Proceedings of the 17th International Joint Conference on Biomedical Engineering Systems and Technologies*, 123–134. <https://doi.org/10.5220/0012363900003657>
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Book chapters

24. Díaz Lantada, A., **Solórzano, W.**, Martínez Cendrero, A., Zapata Martínez, R., Ojeda, C., & Muñoz-Guijosa, J. M. (2022). Methods and technologies for the personalized design of open-source medical devices. In A. Ahluwalia, C. De Maria, & A. Díaz Lantada (Eds.), *Engineering Open-Source Medical Devices: A Reliable Approach for Safe, Sustainable and Accessible Healthcare* (pp. 191–218). Springer International Publishing. https://doi.org/10.1007/978-3-030-79363-0_9
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Final degree theses supervised

26. Co-direction with Prof. Francisco Franco Martínez of the Bachelor's Thesis of Mr. Stephen Mulhern López Oliva, titled: *"Deep learning para la predicción del ángulo de contacto en el diseño de superficies microtexturizadas"*, 2025.
27. Co-direction with Prof. Andrés Díaz Lantada of the Master's Thesis of Mr. Victor Moreno Gutiérrez, titled: *"Desarrollo de autómatas celulares para la generación de estructuras basadas en superficies mínimas triplemente periódicas"*, 2024. This work was awarded an Honorable Mention *ex aequo* in the Innovation Technology Award by the Rodolfo Benito Samaniego Foundation
28. Co-direction with Prof. Andrés Díaz Lantada of the Master's Thesis of Mr. Gabriel Callejo Goena, titled: *"Simulación de la degradación de muelles de PVA mediante autómatas celulares y elementos finitos"*, 2023.
29. Co-direction with Prof. Carlos Ojeda Díaz of the Bachelor's degree final project of Mr. Fernando Javier Tuesta Guzmán, titled: *"Metodología de diseño personalizado de órtesis para el tratamiento de lesiones y fracturas: aplicación a férulas de antebrazo"*, 2023.
30. Co-direction with Prof. Andrés Díaz Lantada of the Bachelor's degree final project of Mr. José Antonio Yáñez González-Cuéllar, titled: *"Diseño personalizado de un vástago femoral corto asistido por redes neuronales convolucionales"*, 2023.
31. Co-direction with Prof. Andrés Díaz Lantada of the Bachelor's degree final project of Mr. Álvaro Morales Sánchez, titled: *"Diseño inteligente de dispositivos médicos personalizados: explorando la eficiencia de la superelipse y el casco convexo"*, 2023.
32. Co-direction with Prof. Andrés Díaz Lantada of the Bachelor's degree final project of Mr. Victor Moreno Gutiérrez, titled: *"Innovación en el diseño personalizado de vástagos humerales cortos"*, 2023.
33. Co-direction with Prof. Andrés Díaz Lantada of the Bachelor's degree final project of Mr. Diego Muñoz García, titled: *"Diseño y fabricación de mecanismos 4D biodegradables para aplicaciones médicas"*, 2023.
34. Co-direction with Prof. Carlos Ojeda Díaz of the Bachelor's degree final project of Mrs. Isabel del Pilar Moscol Albañil, titled: *"Optimización asistida por inteligencia artificial de vástago femoral corto personalizado"*, 2022.

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Appendix A. Glossary for the proposed ontology

Table A.1. Geometries, dimensions and common shapes in shape-morphing & 4D printed actuators.

Common shapes	Geometrical dimensions	Abbreviation
Cube	0D, 3D	C
Bar	1D, 3D	B
Plate	2D, 3D	PL
Cylinder	1D, 3D	CY
Elliptical cylinder	1D, 3DB	ECY
Tube	1D, 3D	T
Disk	2D	DK
Ring	2D	RG
Sphere	0D, 3D	S
Dome	3D	D
Spring	3D	SP
Serpentine spring	1D, 2D	SSP
Torsion spring	2D, 3D	TSP
Letter-bar-shape	2D, 3D	-BS (U-BS)
Letter-cylinder-shape	2D, 3D	-CYS (O-CYS)
Letter-tube-shape	3D	-TS (Y-TS)

Table A.2. Shape-morphing principles classified according to achieved geometrical evolution.

Shape-shifting behaviors/types	Other names	Definitions [259,260]	Abbrev.	Abbrev. v.2
Expansion / contraction [259]	Encapsulation /scaling [260]	Mechanical expansion according to two preferred directions	EXP	EXP/CONT
Swelling / deswelling	Dilation	Three-dimensional expansion through specific volume increase	SW	SW/DSW
Stretching / compressing [260,261]	Shrinkage, deformation [261]-	Mechanical expansion according to a preferred direction	STR	STR/COMP
Folding / unfolding [259]		Folding is a localized deformation with sharp angles within a narrow hinge area [259]	F	F/UF
Bending / straightening [259]		Bending is the overall deformation leading to a smoother curvature [259]	BE	BE/STRA
Rolling / unrolling [259]		Rolling occurs when continuous force is applied, is a motion in which the shape rotates more than 360° on its axis [259]	R	R/UR
Curving / flattening [259]	Waving, curling [2], wrinkling, creasing [1], snapping [260]	Curving is the amount of curvature that deviates from a flat surface of a geometric object [259]	CUR	CUR/FLAT
Topographical change [259]	Pitting, corrosion	Surface topography represents a local/micrometer deviation of the surface from a flat plane [259]	TC	TC
Twisting / untwisting [259]	Torsion	Twisting is dominated by stretching in the plane [259]	TW	TW/UTW

Shape-shifting behaviors/types	Other names	Definitions [259,260]	Abbrev.	Abbrev. v.2
Helixing / unhelixing [259]	Coil, spiral [262,263], spiral [264]	Helix is the type of smooth space deformation with curves occurring in the 3D space [259]	HE	HE/UHE
Buckling / debuckling [259-261]		Buckling is characterized by sudden sideways failure of structural members under high compression stress [259]	BU	BU/DBU
Hierarchical [259]		Mechanism that has several shape shifting types	H	H
Bistable (Multistable)		Structure that has two (or multiple) stable equilibrium positions within the range of motion [265]	BS (MTS)	BS (MTS)
Origami		Origami structure can only change its shape by folding	O	O
Kirigami		Kirigami structure can change its shape by folding and cutting	KI	KI
Kusadama		Kusama involves folding several sheets into identical modules that are then assembled to form a structure	KU	KU
Mechanism (kinematic chain)		Multi-body systems and kinematic chains with kinematic joints	MECHA	MECHA
Metamaterial		Metamaterials are structures rationally designed to enable functionality not found in natural materials [260]	META	META
Auxetic (special family of metamaterials)		It consists of a structure that expands when stretched and contracts when compressed [266]	AUX	AUX

Shape-shifting behaviors/types	Other names	Definitions [259,260]	Abbrev.	Abbrev. v.2
Textile		Textile structure is composed of fibers that are intertwined with each other	TE	TE
Blossoming		This mechanism that allows the unfolding of petal-like structures while maintaining structural integrity	BLO	BLO
Self-assembly		Structures assemble themselves and grow from interconnectable units	SFA	SFA

Table A.3. General scheme of stimuli for actuating smart materials and structures, following [275] with modifications for its adequate adaptation to the proposed codification scheme.

Families of triggering principles	Specific triggering principles or stimuli	Definitions / comments / quotations from references	Abbrev.	
Physical stimuli: Transform the chain dynamics or internal atomic packing arrangements of stimuli-responsive materials, resulting in shape-shifting behavior [276,277].	Mechanical stimuli	Force/ Stress/ Pressure	The materials can deform under the influence of a mechanical force. Also, the internal stress-triggered shape change is driven by the incorporation of the “stress-relaxation” phenomenon during the material manufacturing process [52].	MS-F
		Movement [278] / Vibration	“A tunable, locally resonant structural waveguide is proposed and demonstrated for active vibration bandgap switching and elastic-wave manipulation between 1000–4000 Hz based on 3D printed building blocks of zinc-neutralized poly(ethylene-co-methacrylic acid) ionomer” [279].	MS-V
		Strain/ Deformation	Mechanical-responsive materials with versatile responsiveness and high-end precision detect various regimes of pressure or strain at different positions on the human body during physical activities [280]. A defined strain can be applied to seeded cells during shape recovery and provide dynamic instructions to the scaffold shape [281].	MS-ST
	Fluidic stimuli	“We demonstrate the passive control of viscous flow in a channel by using an elastic arch embedded in the flow. Depending on the fluid flux, the arch may “snap” between two states—constricting and unconstricting—that differ in hydraulic conductivity by up to an order of magnitude” [282]	FS	
	Acoustic stimuli (acoustic field)	Naify et al. [283] explore the intersection of tunable acoustic structures and additive manufacturing by 4D printing a metamaterial	AS	

Families of triggering principles	Specific triggering principles or stimuli	Definitions / comments / quotations from references	Abbrev.
		<p>element whose acoustic response can be locally, actively tuned via resistive heating. Contrary to existing, thermally tunable structures, which rely on ambient heating for elastic modulation, the 3D printed structure presented here can be precisely controlled to selectively soften or stiffen only desired areas of the structure.</p>	
	<p>Electromagnetic stimuli (EM-fields) in some cases with the electrical aspects more presents, in others with the magnetic ones more present</p>	<p>Electric fields have the capability of manipulating cells to predefined positions or orientating cells in particular directions, these phenomena are known as galvanotaxis and electro tropism respectively [277]. Nevertheless, if the applied electric current is too high, it can cause cell death, localized heating, and membrane rupture [276].</p> <p>Electricity is also an indirect stimulus, as it has been proved to show heating effect due to the resistive nature of material through which it passes [275].</p>	ES
		<p>“The shape recovery was actuated as a result of induction heating in the presence of alternating magnetic field” [277]. Furthermore, magnetic field frequency must be in the medical safety range (50–100 kHz) to circumvent the raised temperature that may hurt the body tissue [276,284]. Also, shape-shifting can be realized using magnetic forces, with magnetic dipoles [277].</p> <p>Magnetism-responsive materials have been widely used to design and fabricate various actuation devices due to their excellent mechanical response to an external MF, including magnetic force and torque [52].</p>	MGS

Families of triggering principles	Specific triggering principles or stimuli	Definitions / comments / quotations from references	Abbrev.
		The magnetic field is an direct and indirect stimulus that can bring deformation in the structure [275].	
	Thermal stimuli (heat)	Heat transfer is a direct stimulus. The changes in the shape of these materials are mainly due to two mechanisms: the shape change effect (SCE) or the shape memory effect (SME). In the case of SCE materials, the deformation is proportional to the stimulus applied. The bilayer structure uses the SCE mechanism [275]. A typical 4D structure usually results from the change of molecular structure, anisotropic nature, or different swelling behaviors with the variation of temperature [52].	TS
	Light stimuli (special case of EM stimuli)	The application of light-responsive materials, by selecting specific wavelength, can be characterized into two models: one is the direct light-induced SME, and the other is the indirect effect, whose principal mechanism of action is the photothermal SME (the heat generated from absorbed light) [274,275,277]. Moreover, photo-activated materials are limited, generating responses at a particular wavelength [276].	LS-NIR
			LS-UV
			LS-V
Chemical stimuli: Variations in physiological situations such as a change in pH or ionic concentrations	pH	4D structures shift when the ratio of H ⁺ /OH ⁻ ions in an aqueous solution are varied. The mechanism was attributed to the electrostatic repulsion [52,274]. *pH responsive materials are capable of swelling, shrinking, dissociation or degradation upon change in environmental pH,	pH

Families of triggering principles	Specific triggering principles or stimuli	Definitions / comments / quotations from references	Abbrev.
<p>are usually crucial symptoms for distinguishable kinds of diseases, like cardiovascular system illnesses, infections and cancers; therefore, interpreting them as critical aims of consideration when designing and developing chemical-responsive materials [267,277].</p>	Ionic concentration	<p>attributed to either protonation of ionizable groups or degradation of acid-cleavable bonds [277].</p> <p>Shape morphing could be realized through changing salt concentration. Despite relatively little research on material's response to ionic concentration, it is important to note that physiological electrolytes level can be a critical indication for various diseases [277].</p>	ION
	<p>Biodegradation²⁸ Solvent (dissolution mechanics [261])</p>	<p>The solvent-induced stimulus is relatively easy because a 4D construct can achieve the shape transformation or functional transformation only through immersion into a solvent such as water [52].</p> <p>This mechanism was demonstrated by Kokkinis et al. [285] in the field of bioprinting. In this mechanism, a printed structure is immersed in an appropriate solvent (ethyl acetate), based on the studied polymer structures. A change in shape occurs as a result of the loss of some non-crosslinked polymers when the structure is immersed in the solvent [261].</p>	BIODEG
	Humidity/Moisture	<p>Printed structures change their shape when they absorb water and recover their original shape after drying [274].</p> <p>For liquid-responsive materials, transformation is designed such that differential swelling of the different compartments occurs in spatially and temporally dependent manner [276,277].</p>	MO

²⁸ If degradation is the triggering stimulus, the abbreviation used will be DEG.

Families of triggering principles	Specific triggering principles or stimuli	Definitions / comments / quotations from references	Abbrev.	
<p>Biological stimuli: In the human body, biological processes often rely on feedback-controlled communication involving biological small molecules or biomacromolecules such as glucose, enzymes, nucleic acids, polypeptides, and proteins [276,277].. All play a significant role in controlling the normal mechanism and functioning of organs. Therefore, recognizing these important parameters and biomaterials that respond to biological stimuli are essential for the better performance of 4D printing technology [267].</p>	Biological scavenging	<p>Enzymatic degradable materials are also of significant interest in the field of tissue regeneration because implants made of these materials can be broken down and removed naturally from the body after they have fulfilled their functions [277].</p> <p>However, weak mechanical strength, slow response time, and hydrolysis can cause degradation, and swelling/de-swelling cycles are essential considerations when estimating the material's usage and life span [276].</p>	BIOSCA	
	Cell traction force [274]	<p>Living materials incorporating cells within synthetic chassis, with the cells acting mechanically upon the chassis and moving them.</p>	CTF	
	Enzymes [274,276]	<p>Shape-shifting processes at molecular level.</p>		
	Glucose [276]			
	Proteins [276]			
	Polypeptides [276]			NANO
	Nucleic acids [276]			
	Glucose [276]			
Proteins [276]				

Table A.4. Common families of materials and shape memory [261,267,272] materials, with which shape-morphing systems and 4D printed actuators can be created.

Family	Materials	Abbreviation
Common materials	Alloys	A
	Polymers	P
	Composites	CO
	Multimaterials	MT*
	Ceramics	CE
	Gels	G
	Carbons	CA
Shape memory (SM) materials	Alloys	A (SMA)
	Polymers	P
	Composites	CO
	Multimaterials	MT*
	Ceramics	CE
	Gels	G
	Carbons	CA

* When defining 4D printed actuator that is multimaterial, the component materials are added as follows: MT(CE+P+...)

Table A.5. The ontology and codification scheme, as regards additive manufacturing technologies, is based on the 7-family division commonly accepted [274], with some minor modifications. The Table below includes the glossary of selected relevant additive manufacturing technologies for the proposed ontology and codification scheme.

Technology	AM process	Abbreviation	Reference
Material extrusion EXT	Fused filament fabrication	FFF	[273,274]
	Direct ink writing	DIW	[273]
Material jetting JET	Nano particle jetting	NPJ	[273]
	Drop on demand	DOD	[273]
Vat polymerization VAT	Stereolithography	SLA	[273,274]
	Continuous direct light processing	CDLP	[273,274]
	Digital light processing	DLP	[273,274]
Binder jetting BIN	Binder jetting	BJ	[274]
	Inkjet head printing		
Powder bed fusion PBF	Multi jet fusion	MFJ	[274]
	Electron beam melting	EBM	[273,274]
	Selective laser melting	SLM	[273,274]

Technology	AM process	Abbreviation	Reference
	Selective laser sintering	SLS	[273,274]
	Laser engineered net shaping	LENS	[273,274]
Direct energy deposition DED	Laser metal deposition	LMD	[273]
	Cold metal transfer	CMT	[273]
	Rapid plasma deposition	RPD	[273]
	Electron-beam additive manufacturing	EBAM	[274]
	Laminated object manufacturing	LOM	[273,274]
Sheet lamination LAM	Solid foil polymerization	SFP	[273]
	Ultrasonic additive manufacturing	UAM	[273]

Appendix B. Shape changes in the mechanisms of the 4D actuator library triggered by degradation

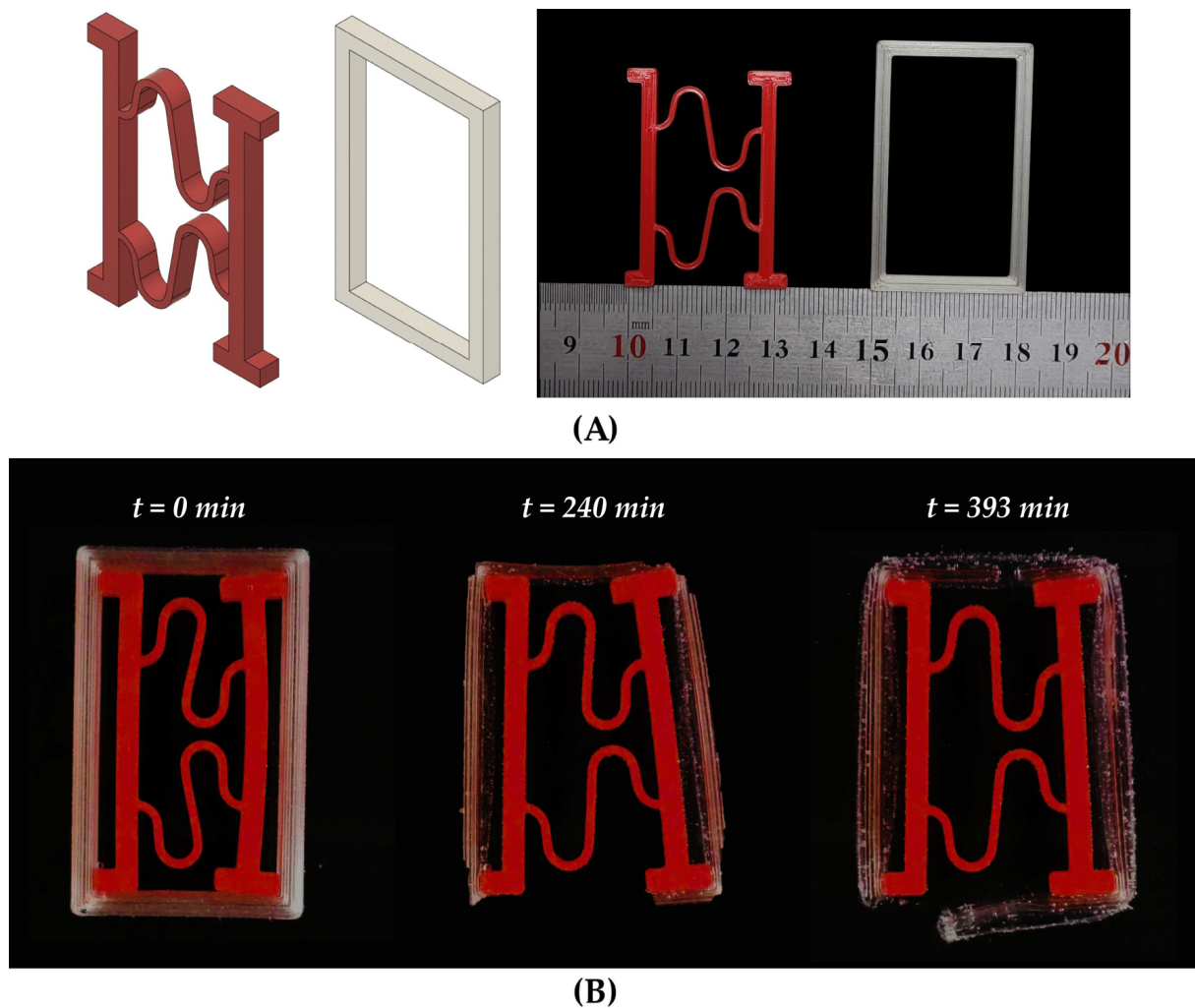
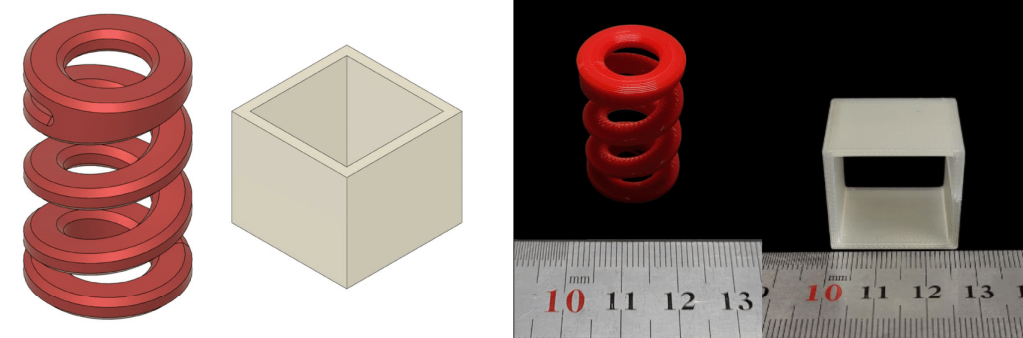
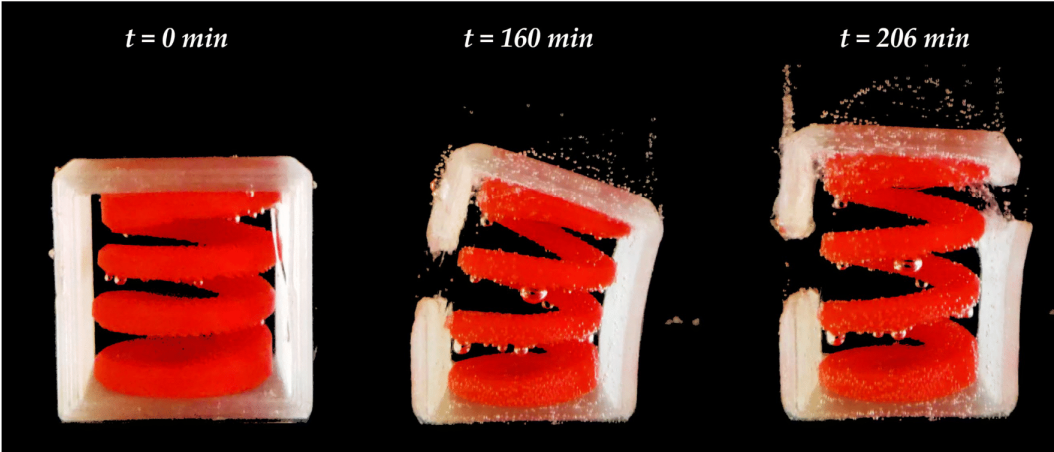


Figure B.1. (A) CAD models & prototypes and (B) shape-morphing test for actuator 1.

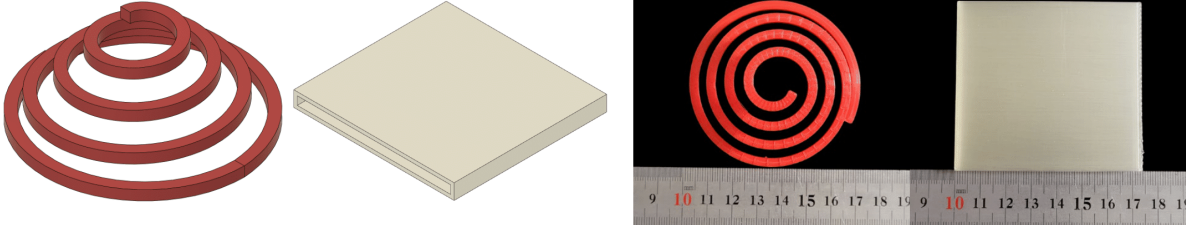


(A)

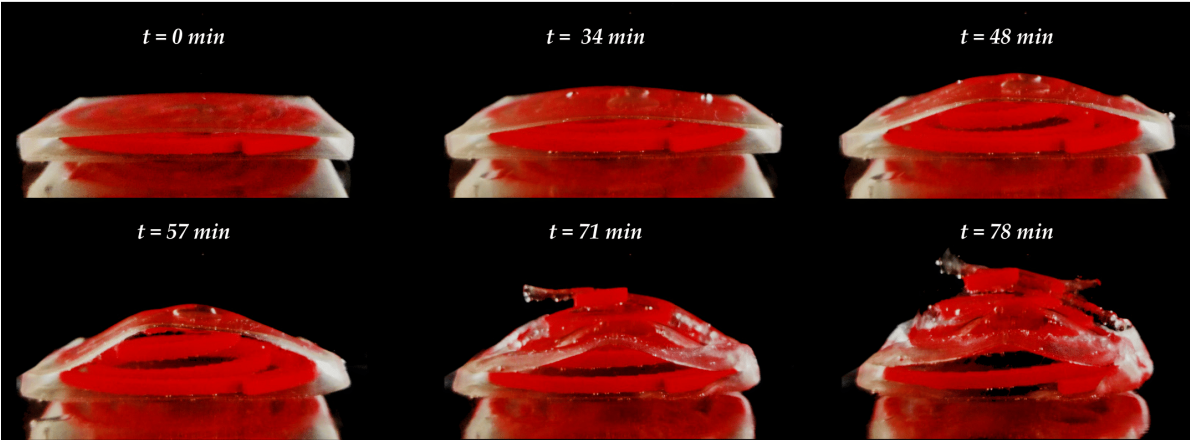


(B)

Figure B.2. (A) CAD models & prototypes and (B) shape-morphing test for actuator 2.



(A)



(B)

Figure B.3. (A) CAD models & prototypes and (B) shape-morphing test for actuator 3.

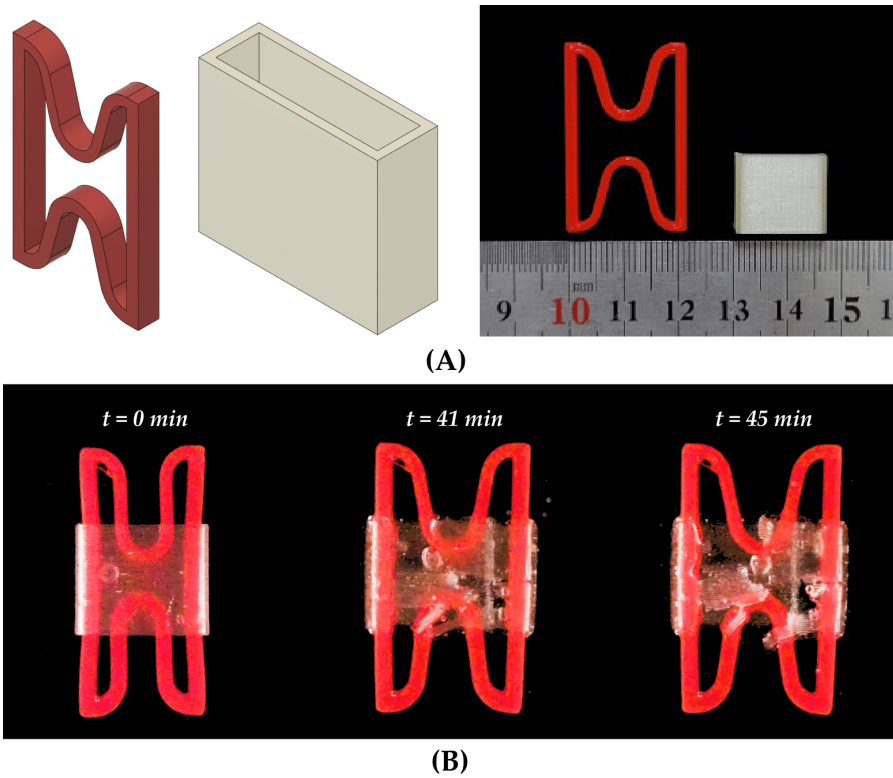


Figure B.4. (A) CAD models & prototypes and (B) shape-morphing test for actuator 4.

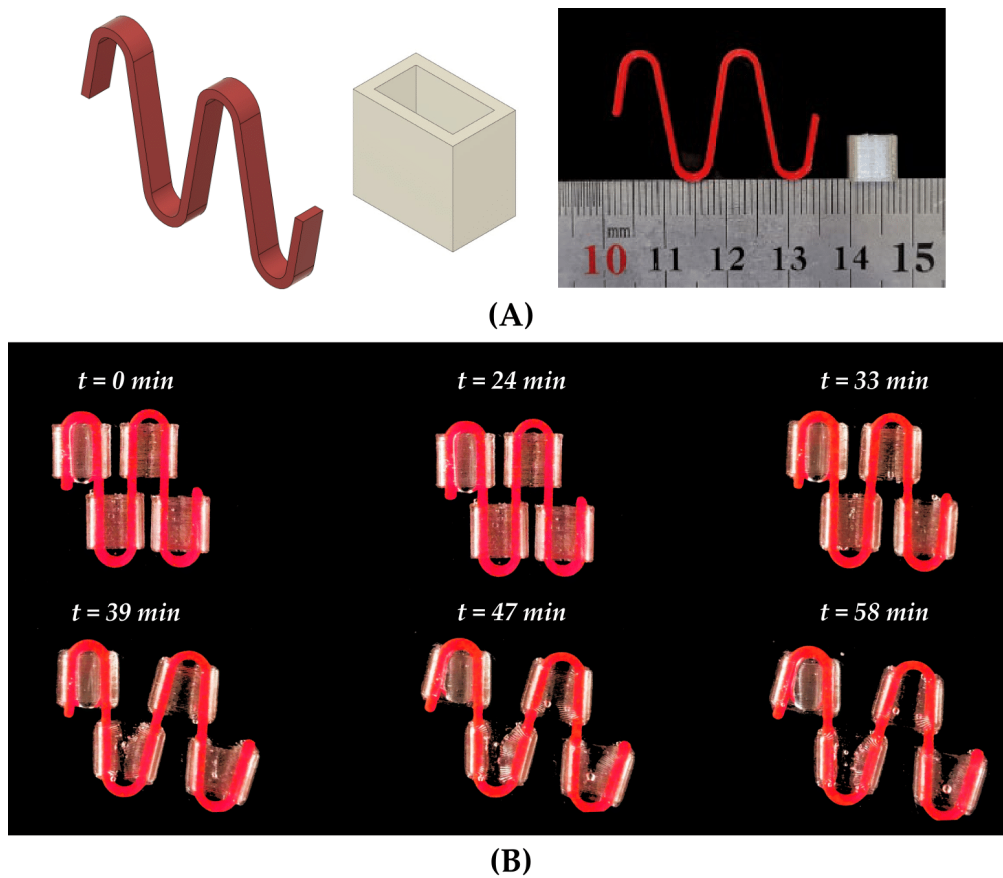


Figure B.5. (A) CAD models & prototypes and (B) shape-morphing test for actuator 5.

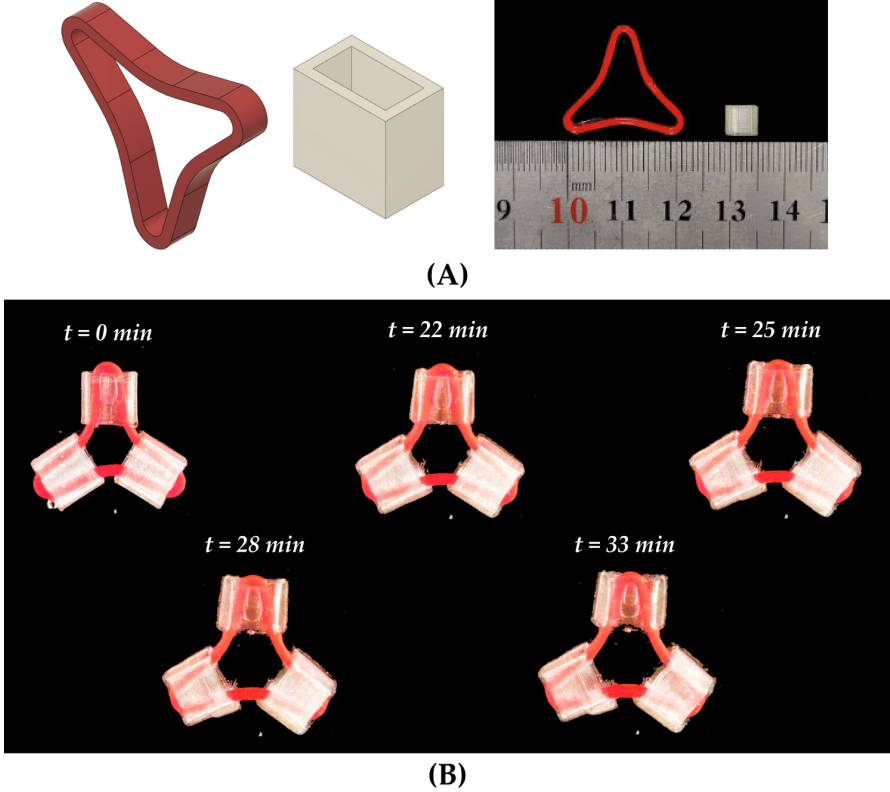


Figure B.6. (A) CAD models & prototypes and (B) shape-morphing test for actuator 6.

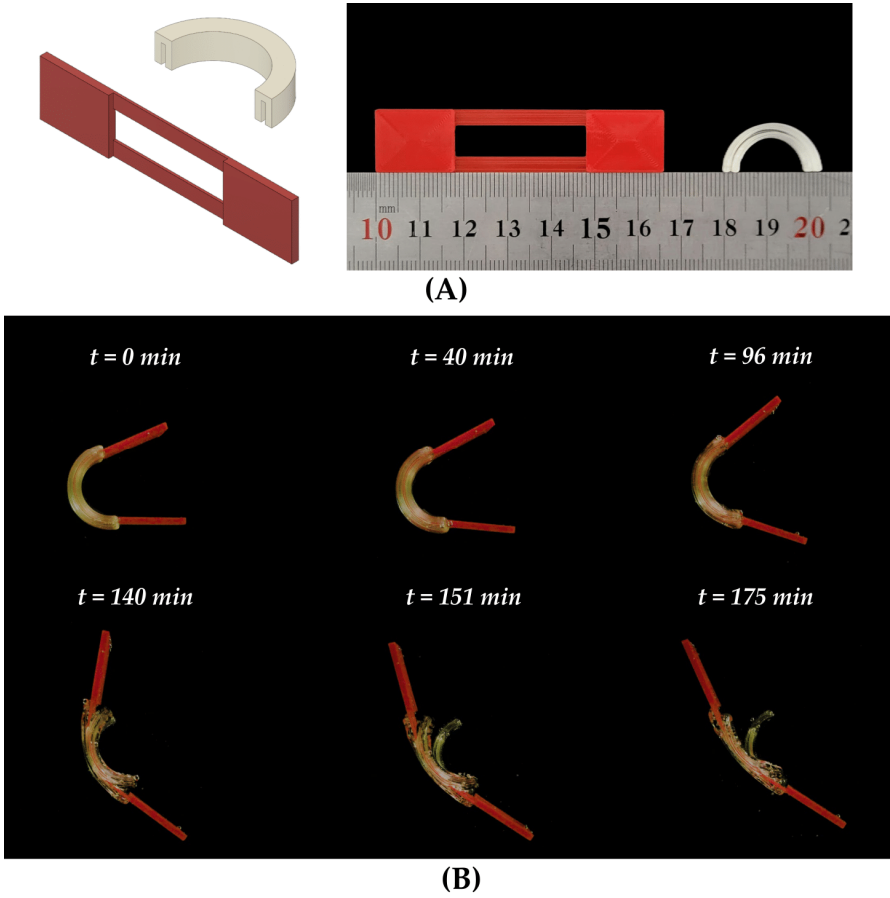


Figure B.7. (A) CAD models & prototypes and (B) shape-morphing test for actuator 7.

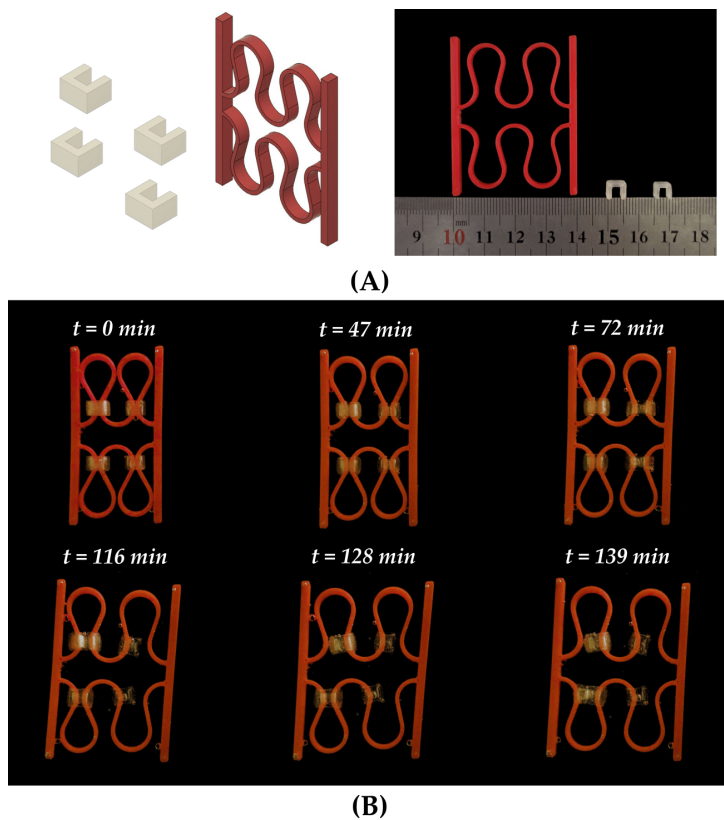


Figure B.8. (A) CAD models & prototypes and (B) shape-morphing test for actuator 8.

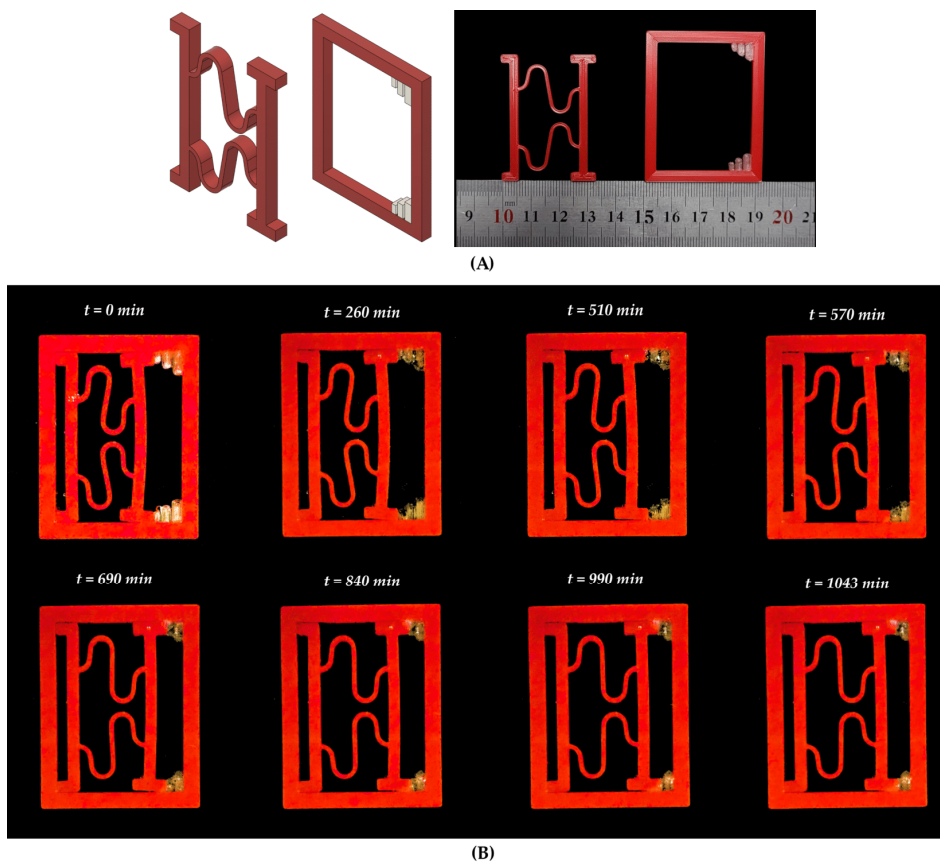


Figure B.9. (A) CAD models & prototypes and (B) shape-morphing test for actuator 9.

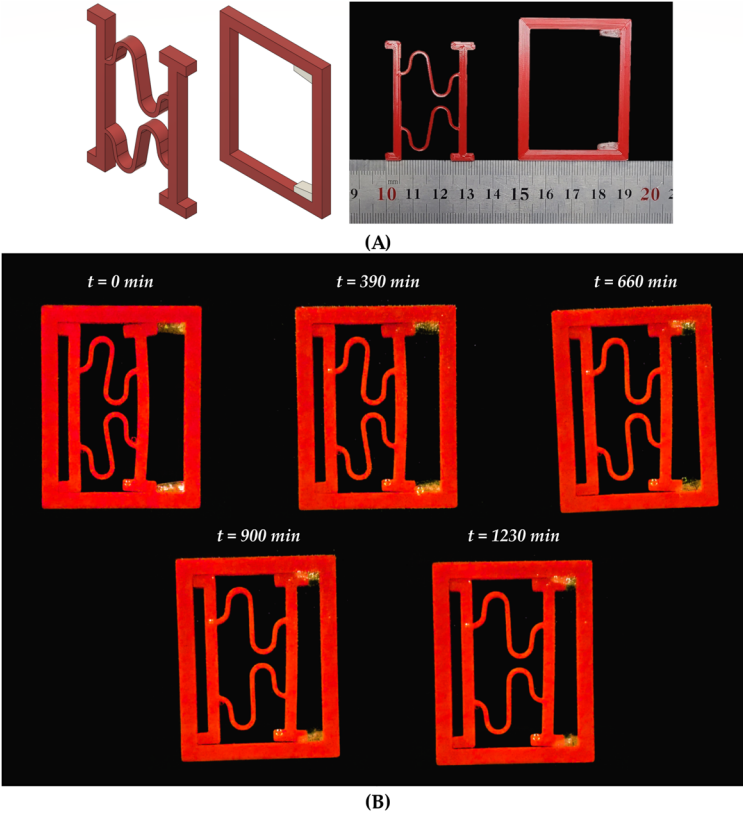


Figure B.10. (A) CAD models & prototypes and (B) shape-morphing test for actuator 10.

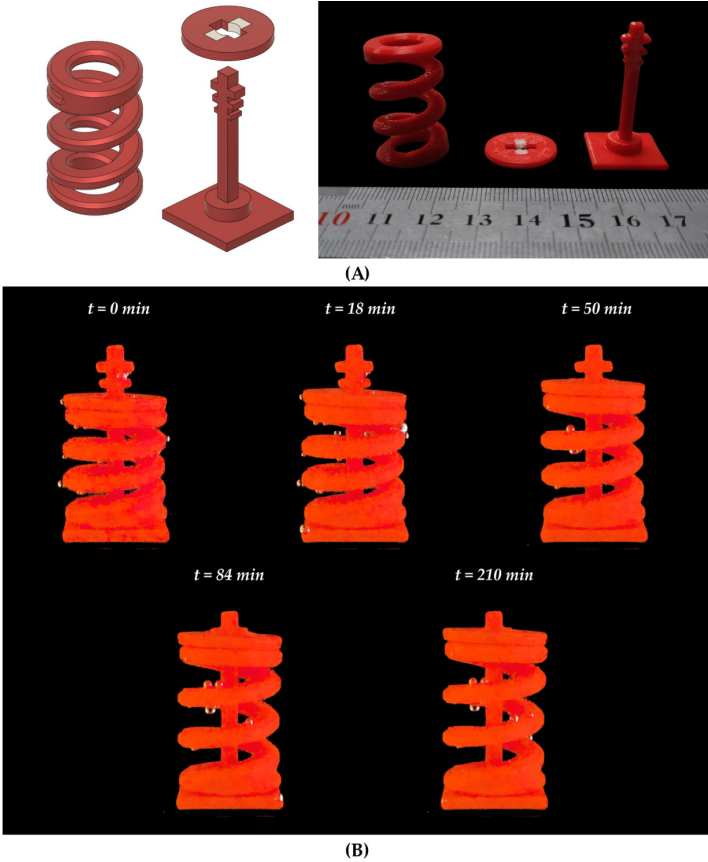


Figure B.11. (A) CAD models & prototypes and (B) shape-morphing test for actuator 11.

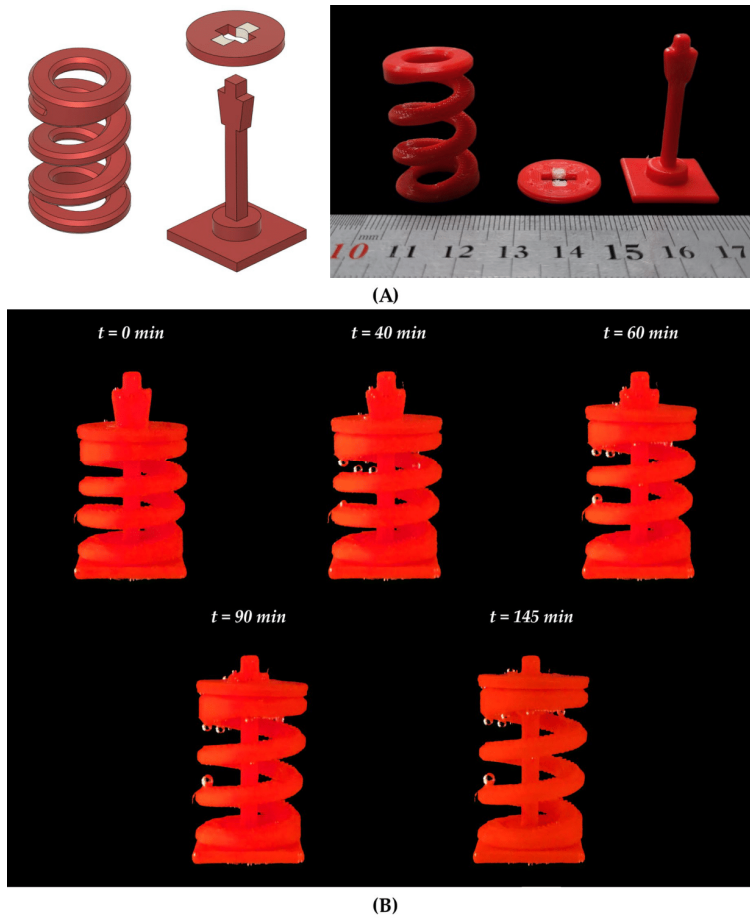


Figure B.12. (A) CAD models & prototypes and (B) shape-morphing test for actuator 12.

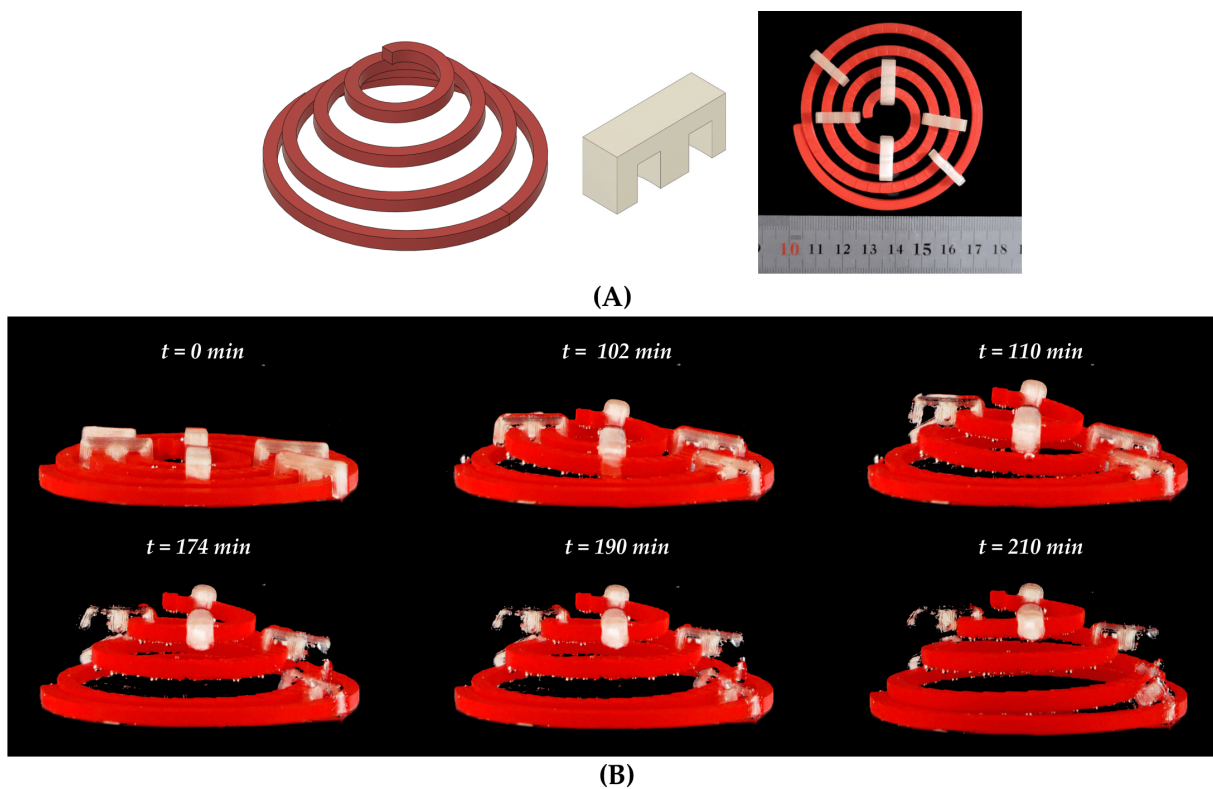


Figure B.13. (A) CAD models & prototypes and (B) shape-morphing test for actuator 13.

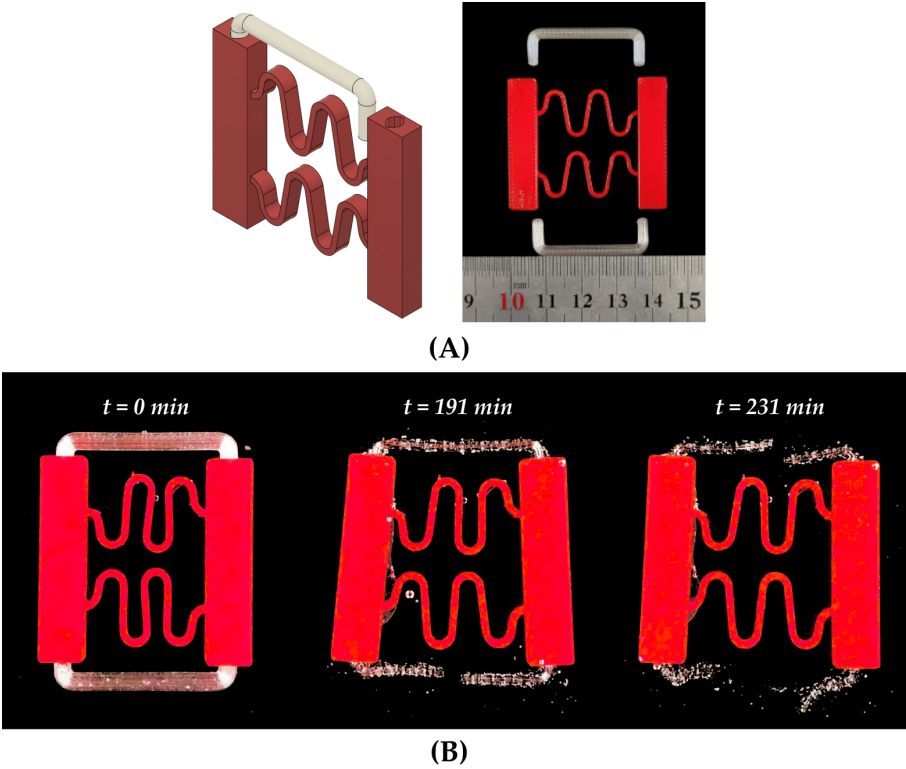


Figure B.14. (A) CAD models & prototypes and (B) shape-morphing test for actuator 14.

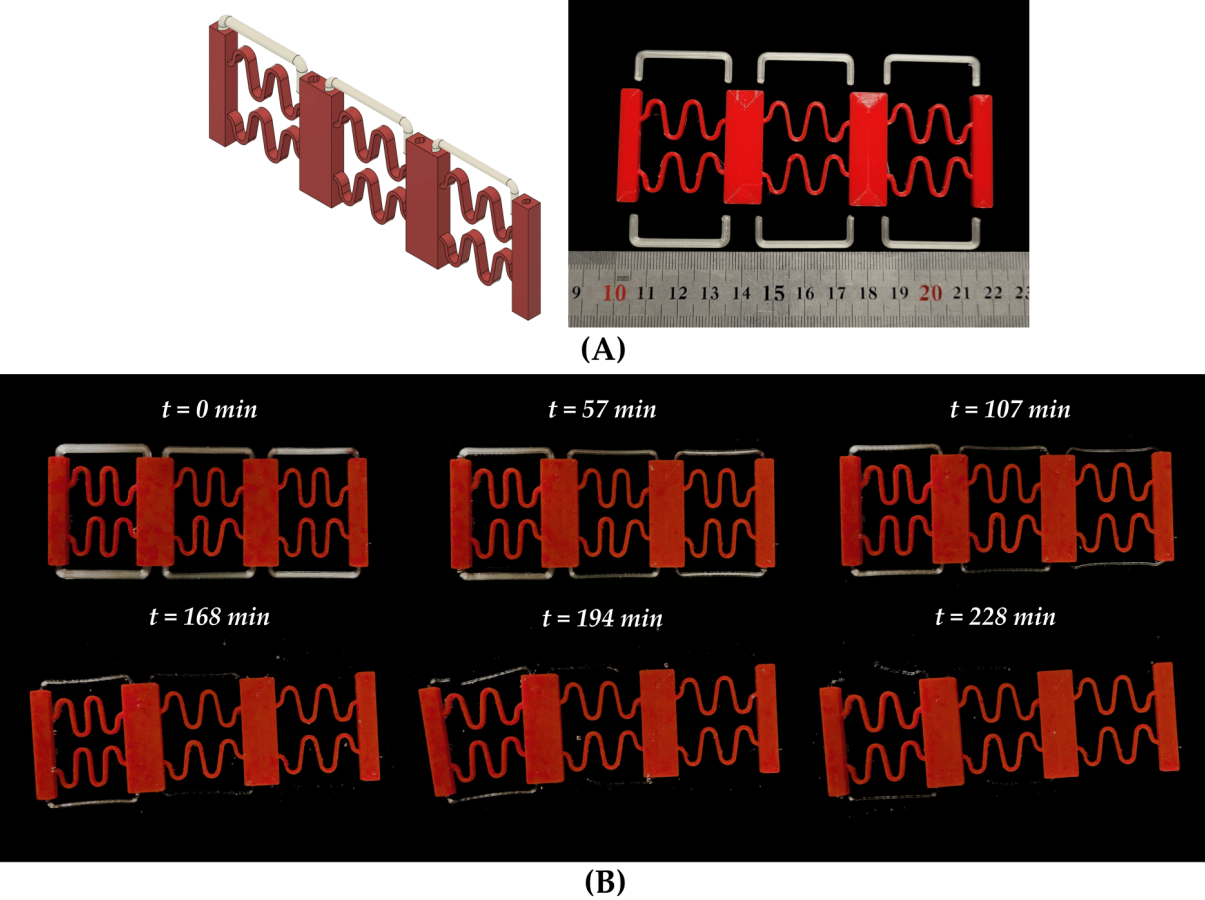


Figure B.15. (A) CAD models & prototypes and (B) shape-morphing test for actuator 15.

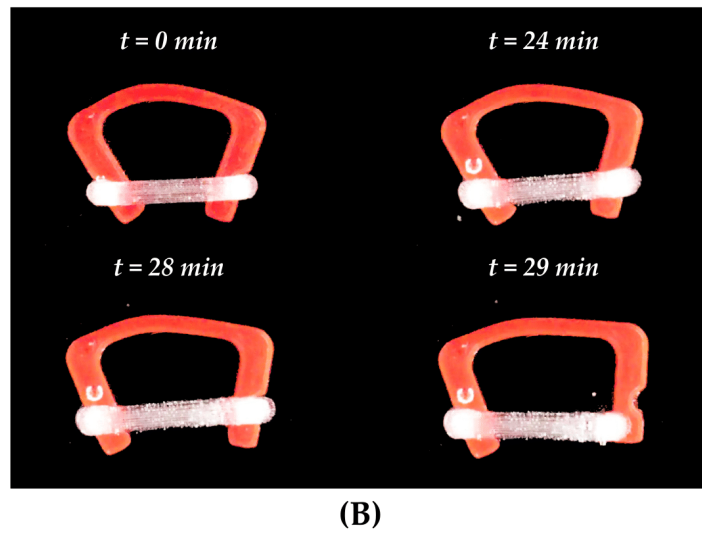
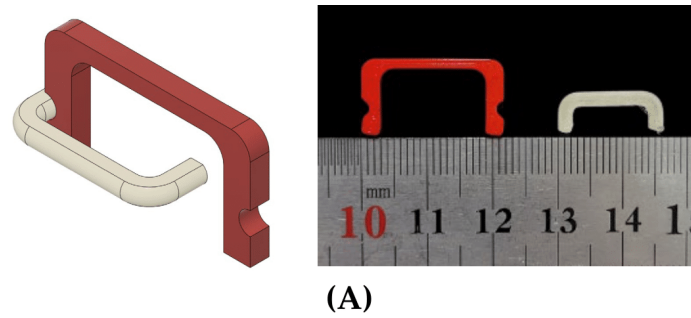


Figure B.16. (A) CAD models & prototypes and (B) shape-morphing test for actuator 16.

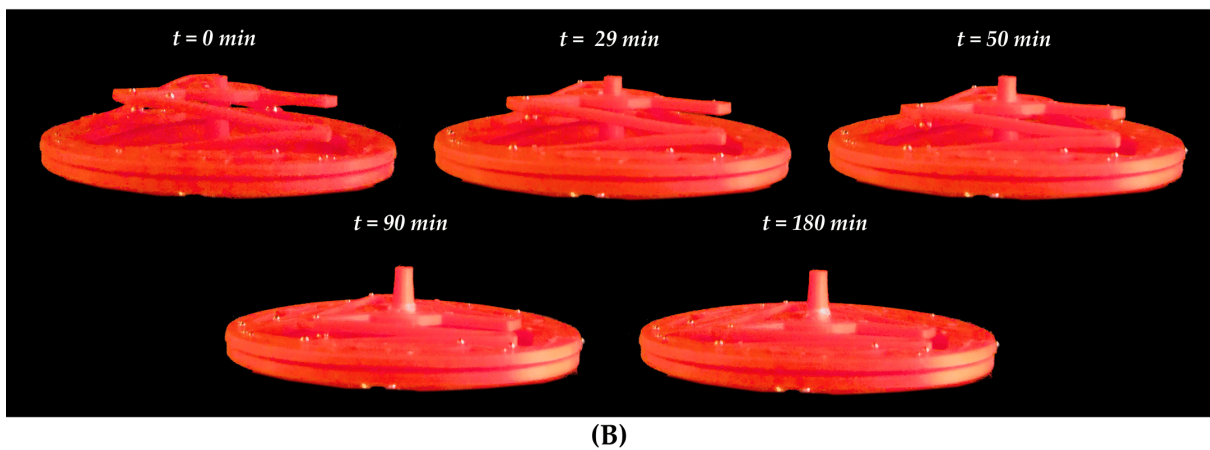
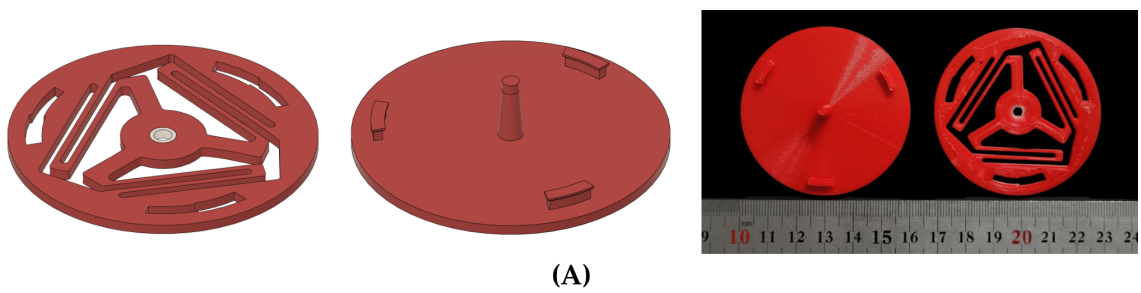


Figure B.17. (A) CAD models & prototypes and (B) shape-morphing test for actuator 17.

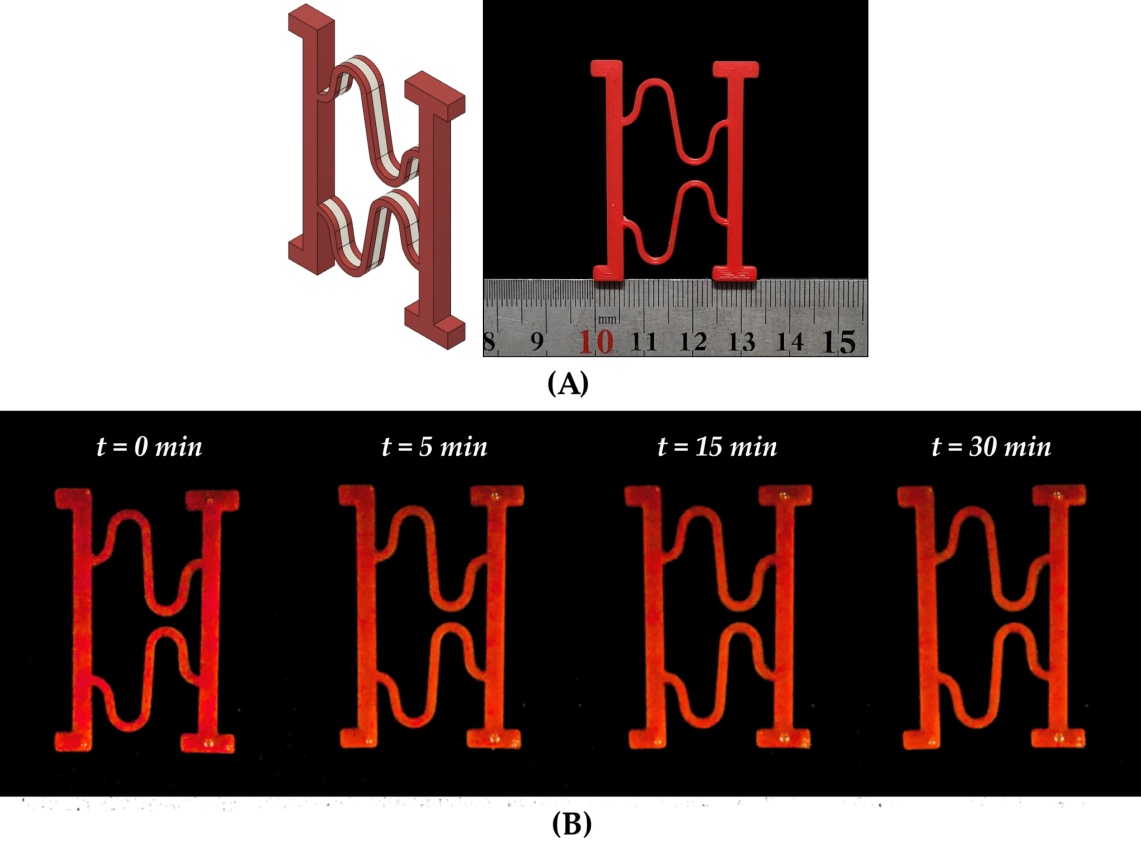


Figure B.18. (A) CAD models & prototypes and (B) shape-morphing test for actuator 18.

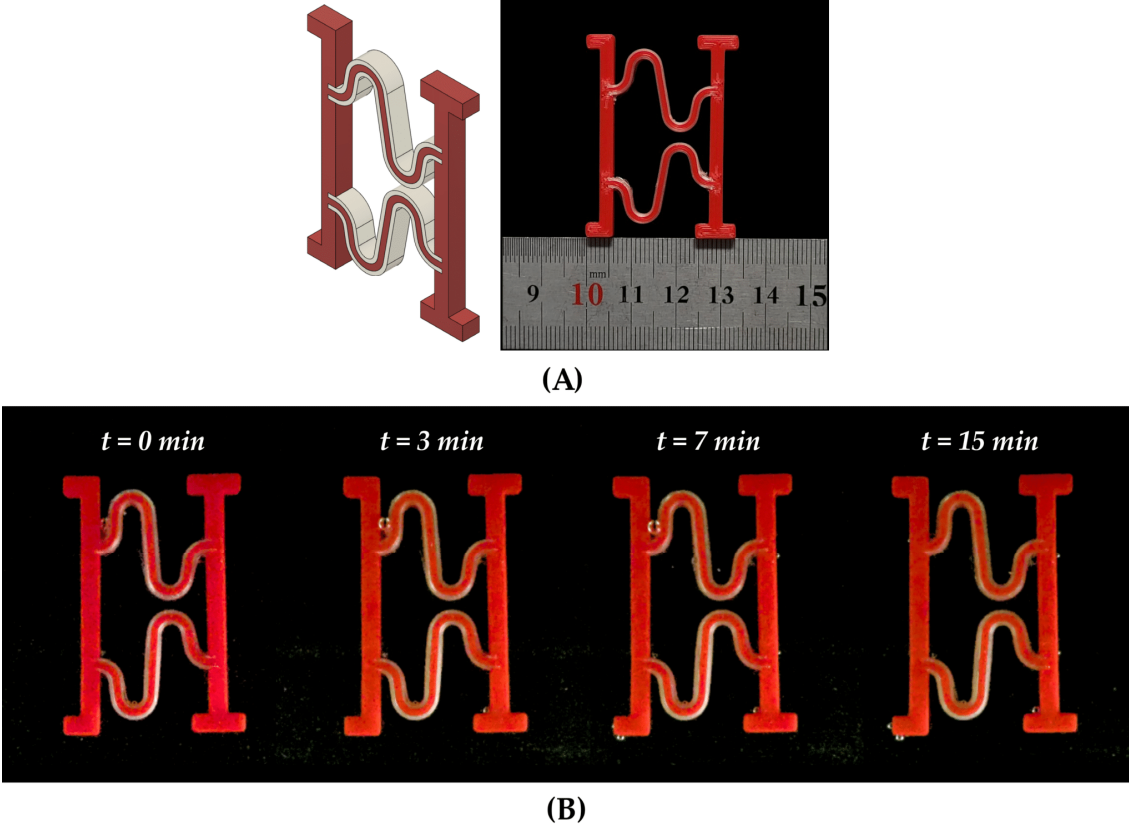


Figure B.19. (A) CAD models & prototypes and (B) shape-morphing test for actuator 19.

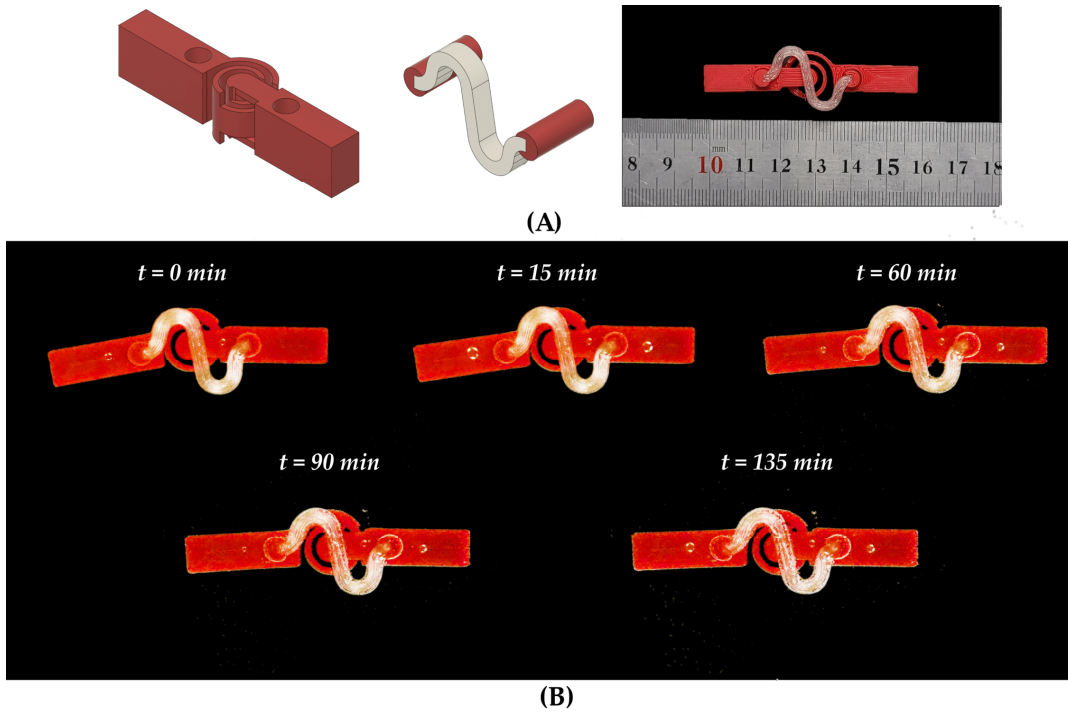


Figure B.20. (A) CAD models & prototypes and (B) shape-morphing test for actuator 20.

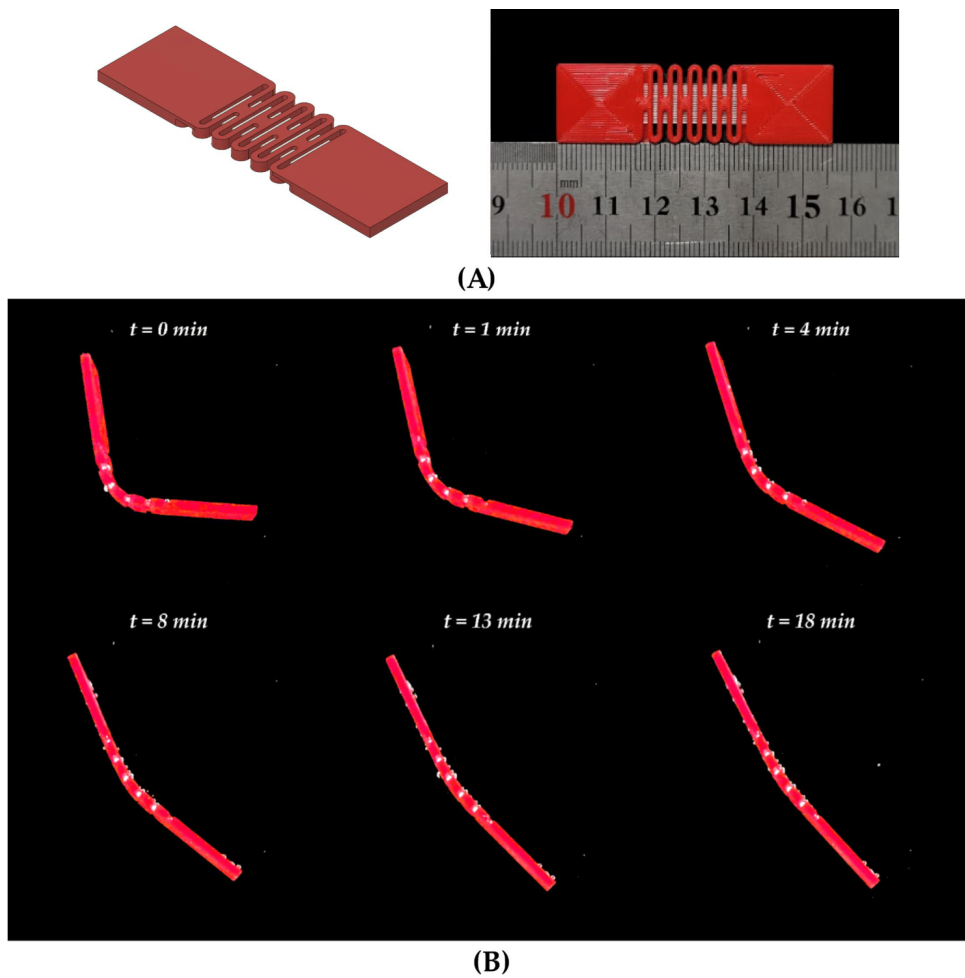


Figure B.21. (A) CAD models & prototypes and (B) shape-morphing test for actuator 21.

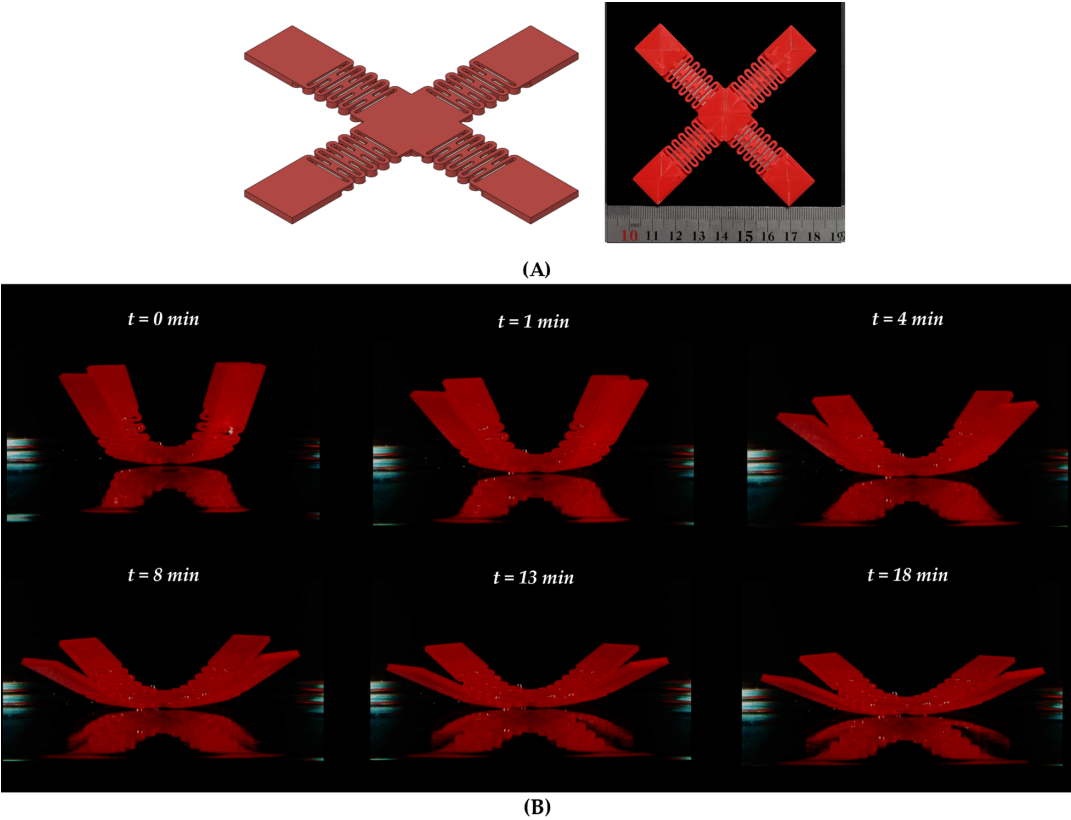


Figure B.22. (A) CAD models & prototypes and (B) shape-morphing test for actuator 22.

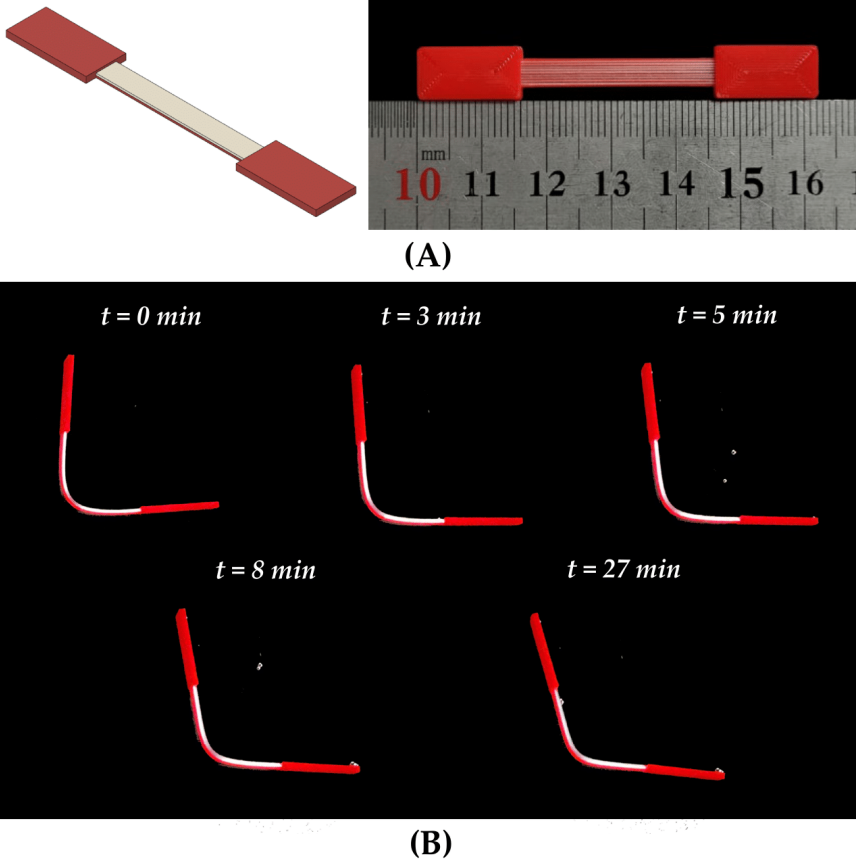


Figure B.23. (A) CAD models & prototypes and (B) shape-morphing test for actuator 23.

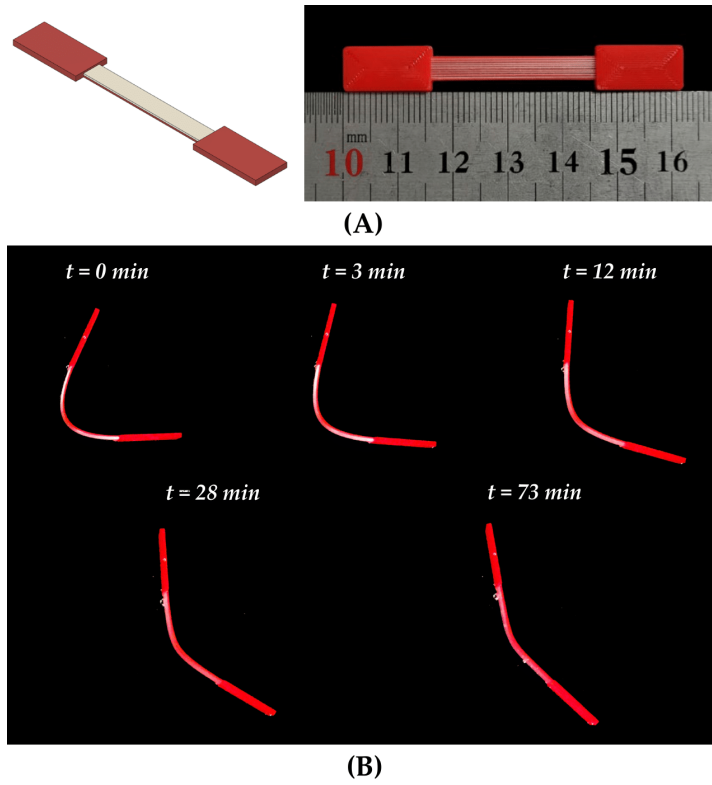


Figure B.24. (A) CAD models & prototypes and (B) shape-morphing test for actuator 24.

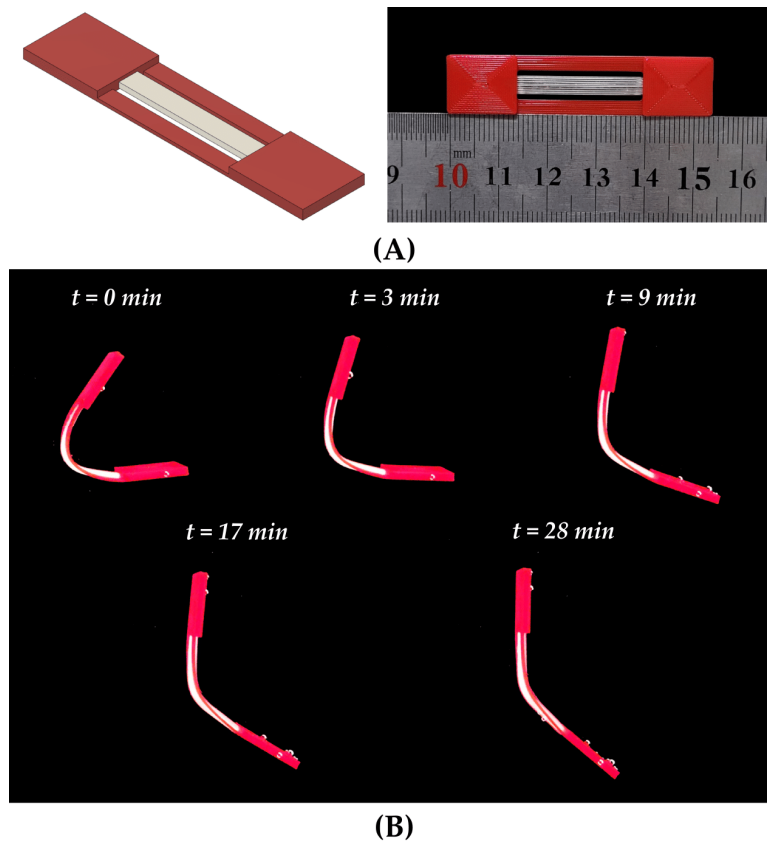


Figure B.25. (A) CAD models & prototypes and (B) shape-morphing test for actuator 25.

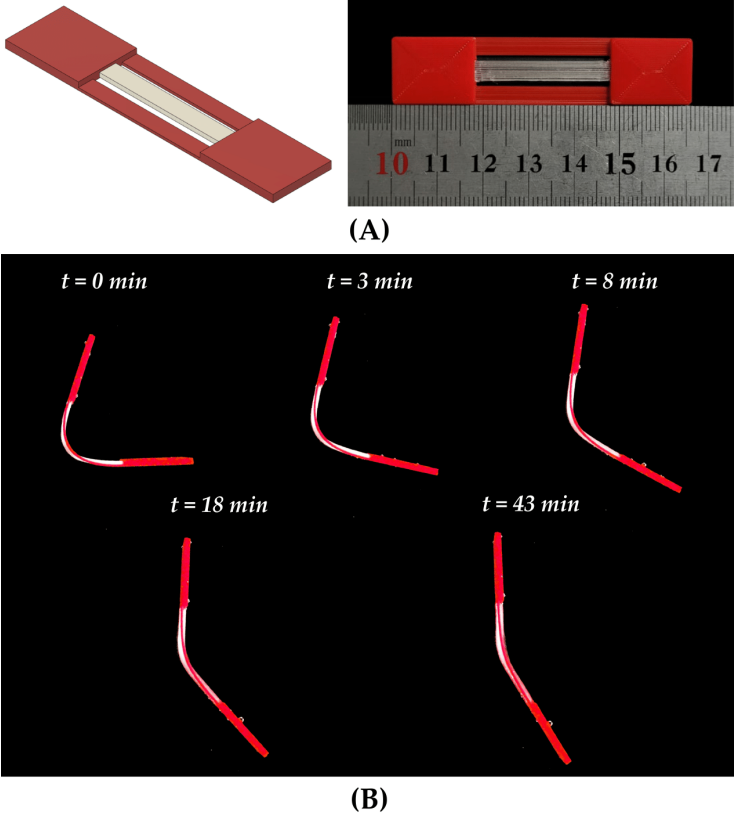


Figure B.26. (A) CAD models & prototypes and (B) shape-morphing test for actuator 26.

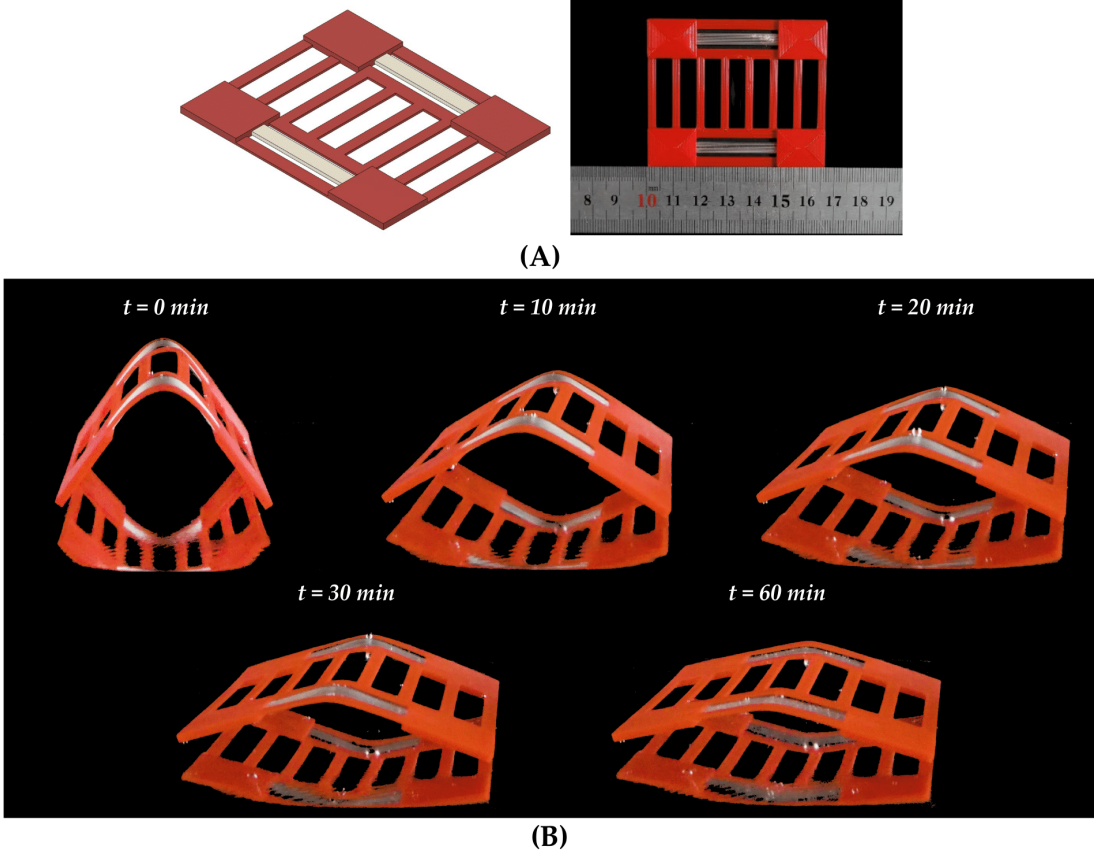


Figure B.27. (A) CAD models & prototypes and (B) shape-morphing test for actuator 27.

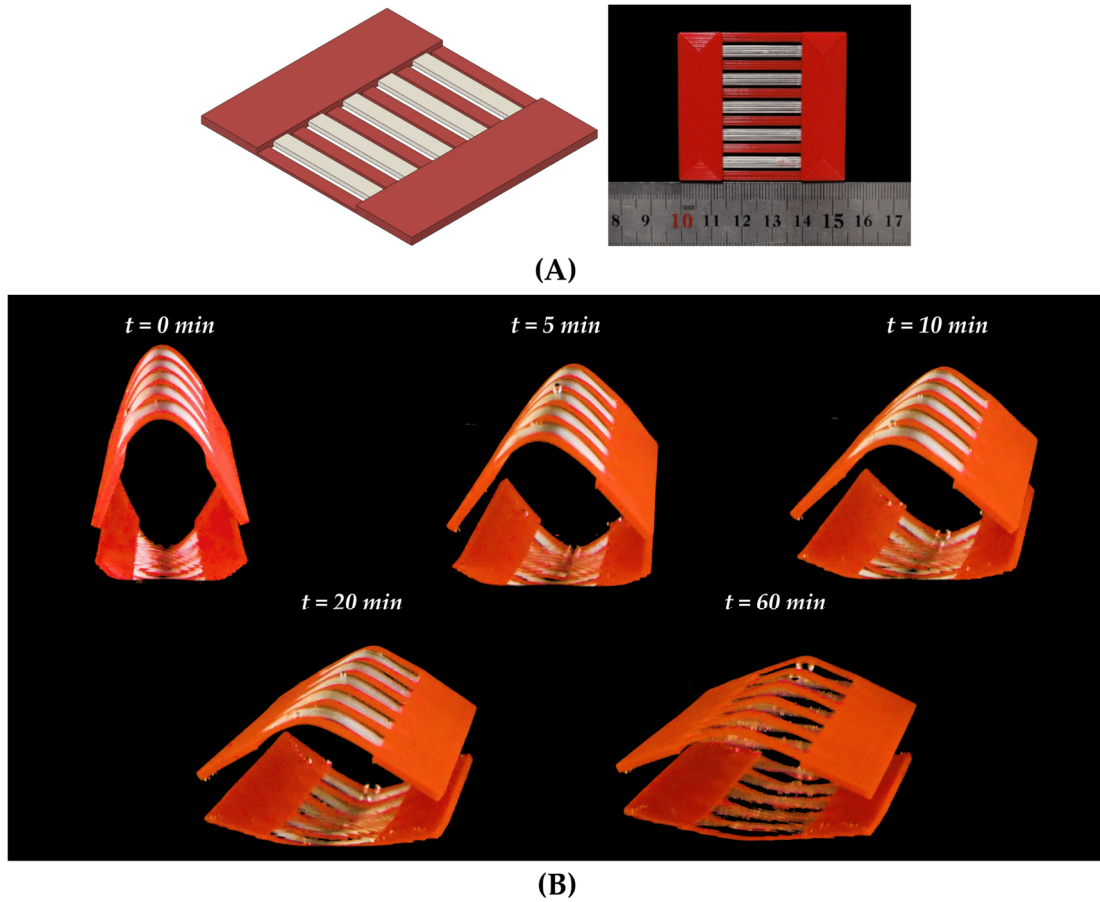


Figure B.28. (A) CAD models & prototypes and (B) shape-morphing test for actuator 28.

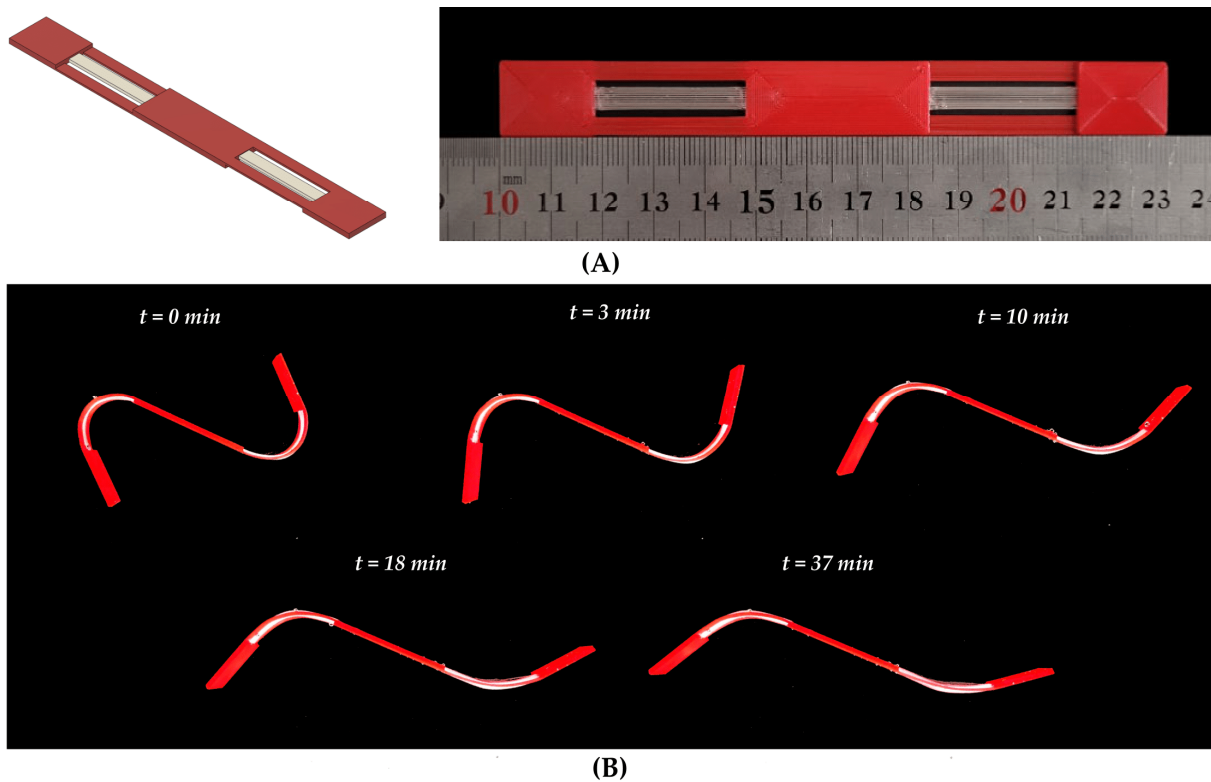


Figure B.29. (A) CAD models & prototypes and (B) shape-morphing test for actuator 29.

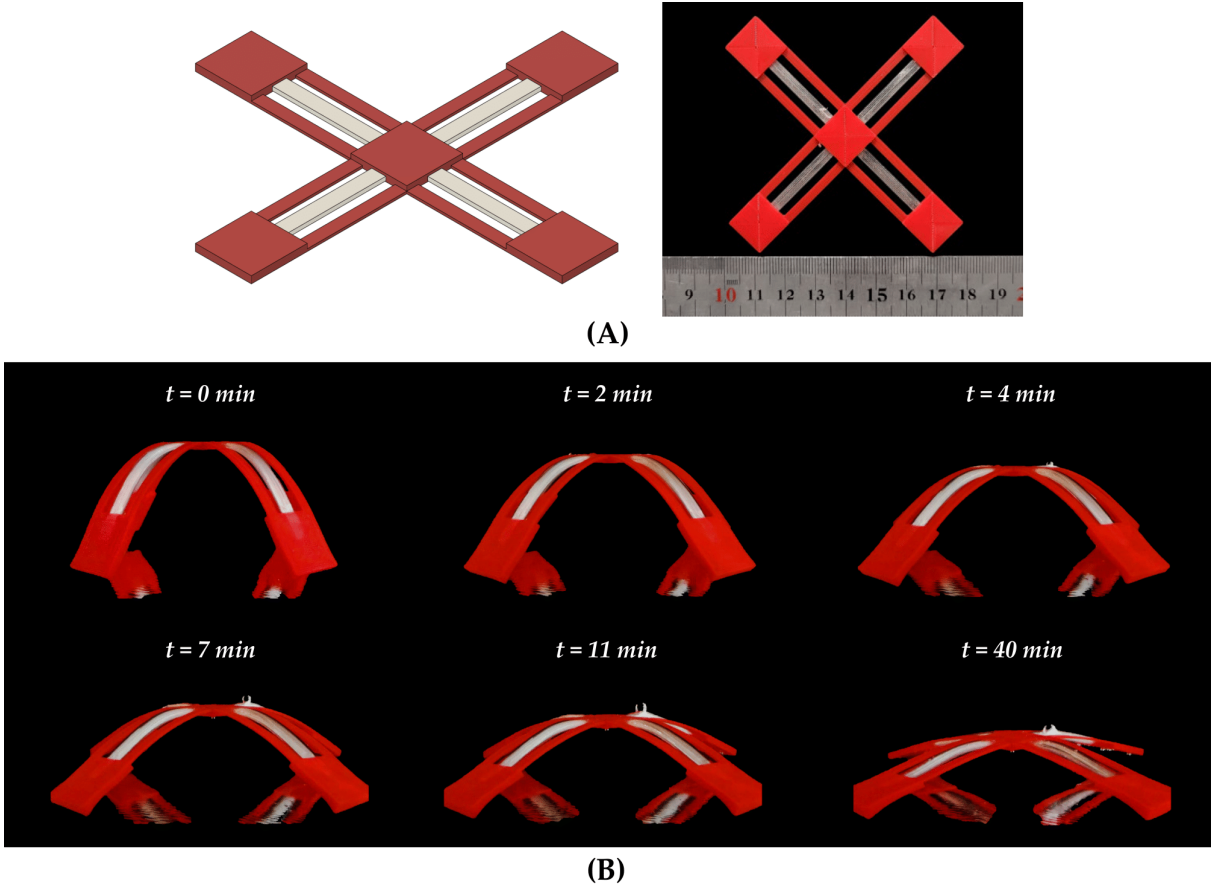


Figure B.30. (A) CAD models & prototypes and (B) shape-morphing test for actuator 30.

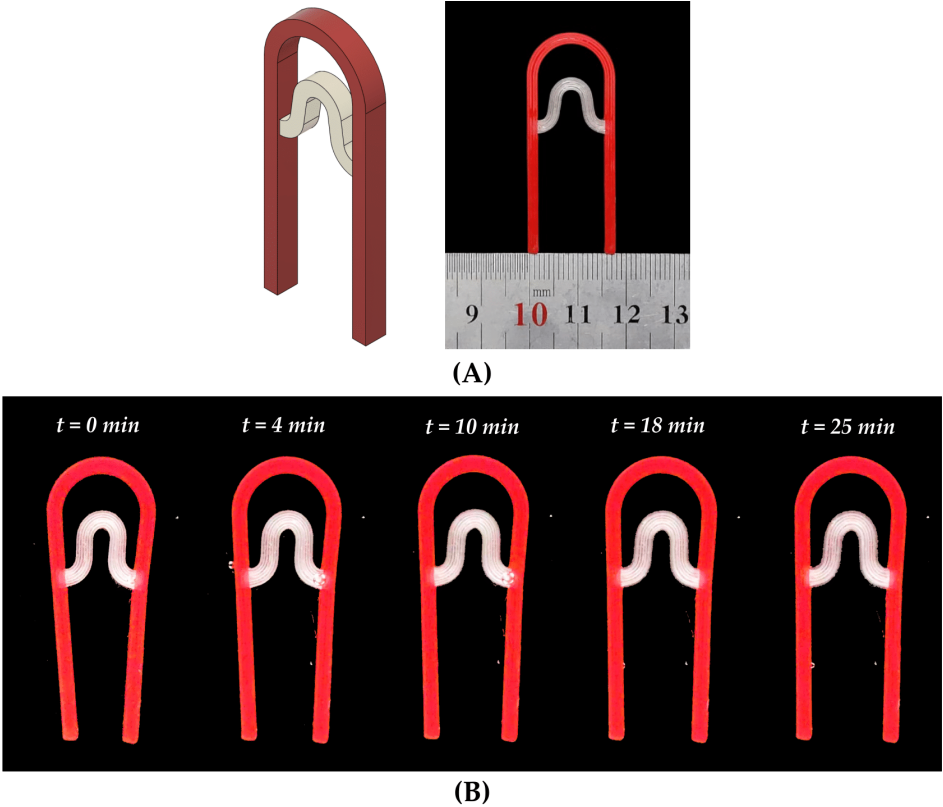


Figure B.31. (A) CAD models & prototypes and (B) shape-morphing test for actuator 31.

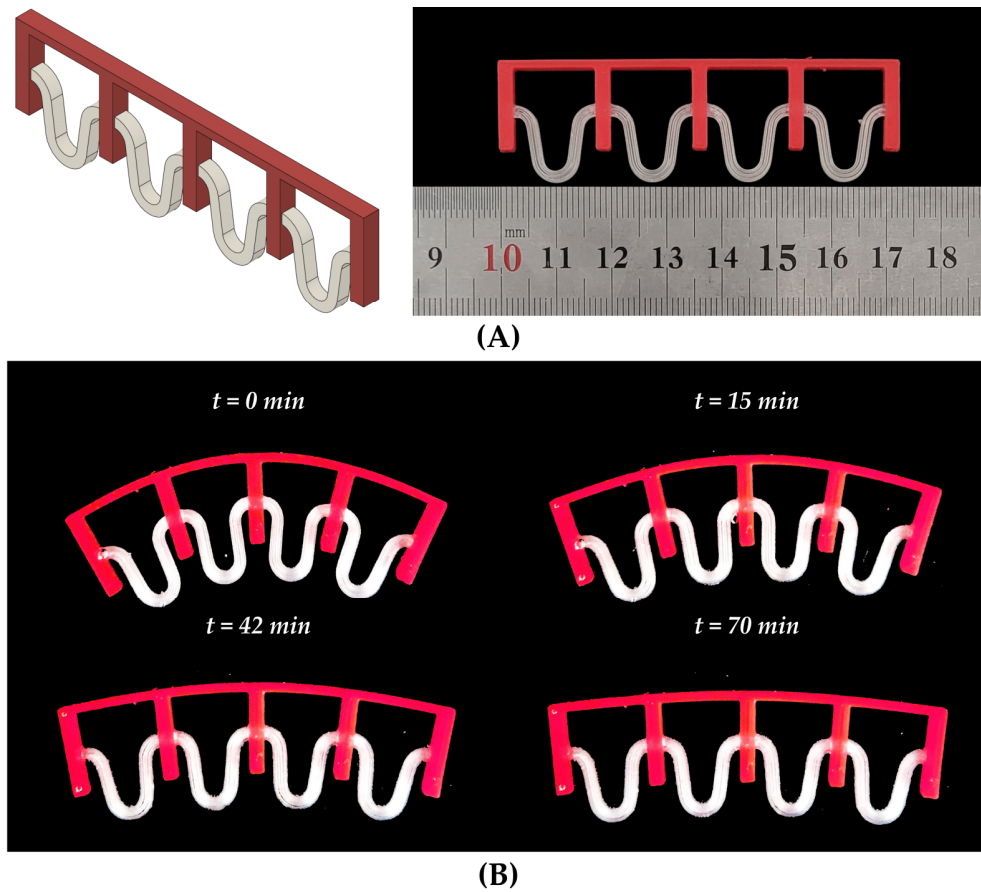


Figure B.32. (A) CAD models & prototypes and (B) shape-morphing test for actuator 32.

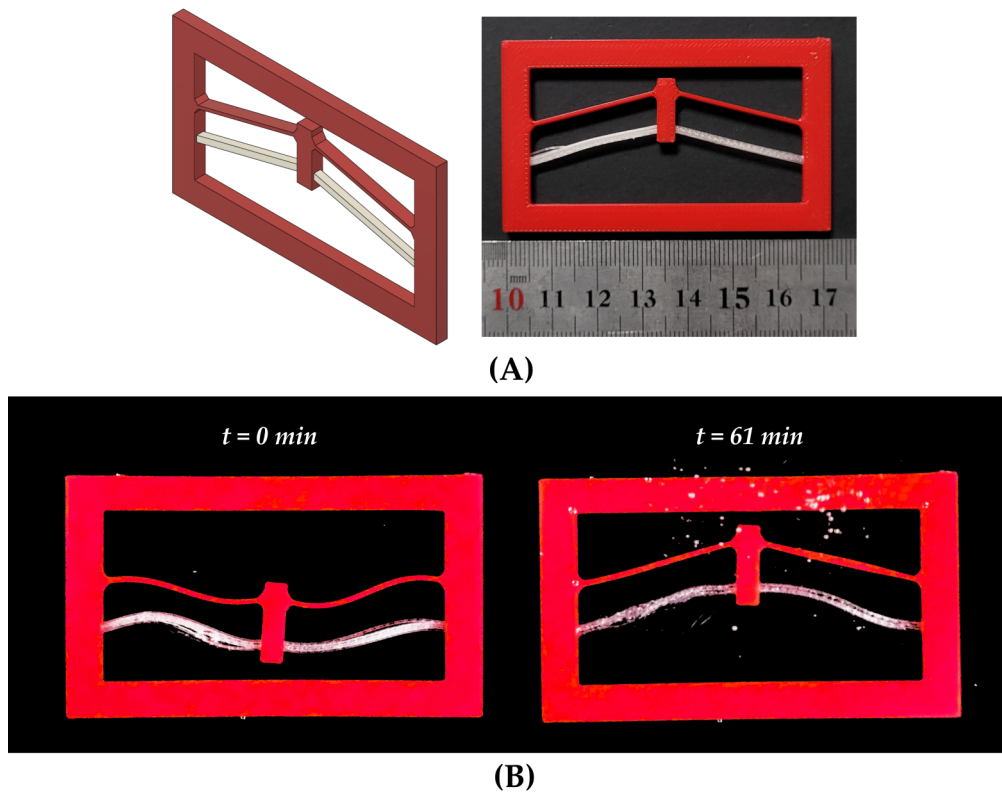


Figure B.33. (A) CAD models & prototypes and (B) shape-morphing test for actuator 33.

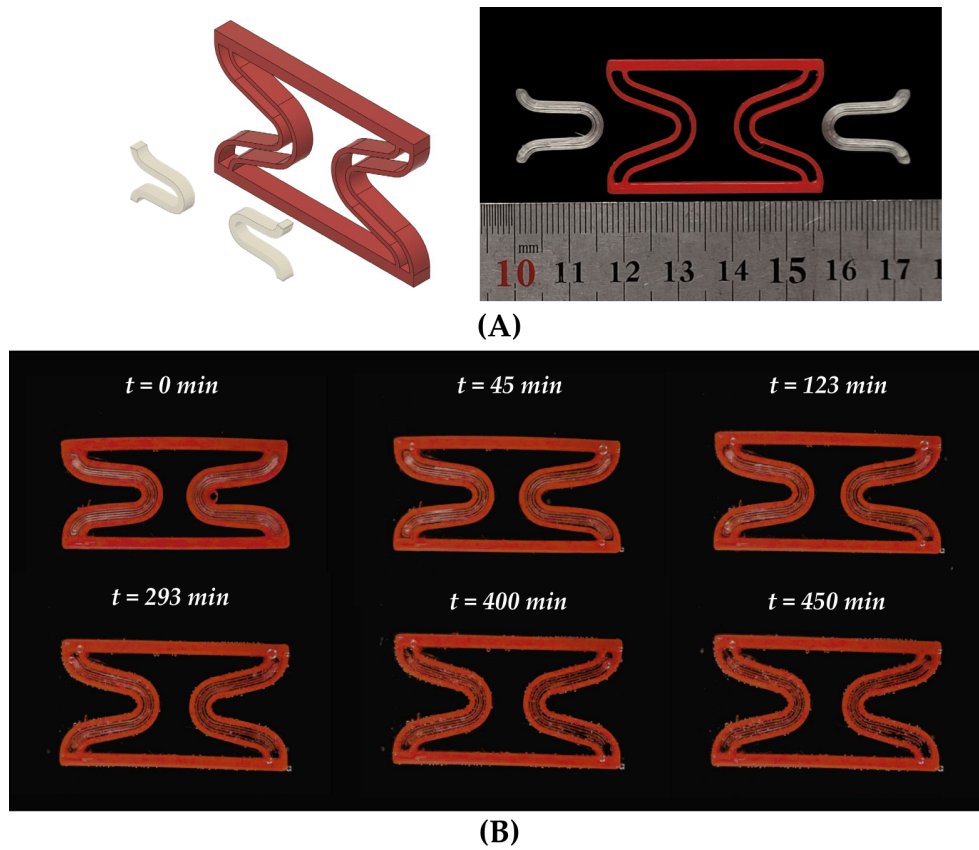


Figure B.34. (A) CAD models & prototypes and (B) shape-morphing test for actuator 34.

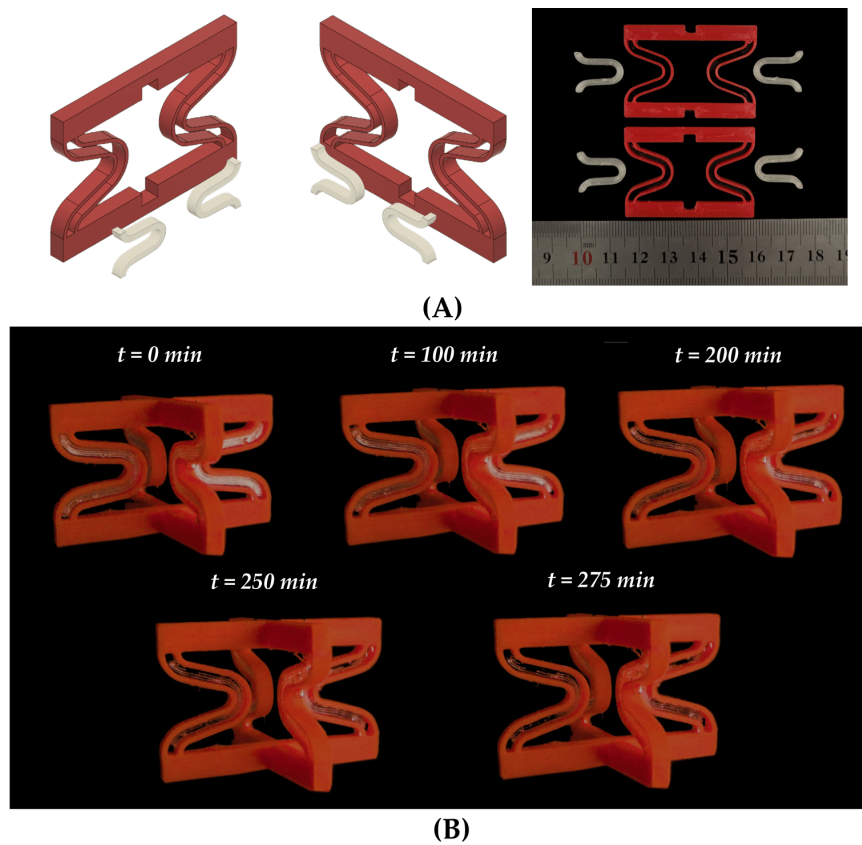


Figure B.35. (A) CAD models & prototypes and (B) shape-morphing test for actuator 35.

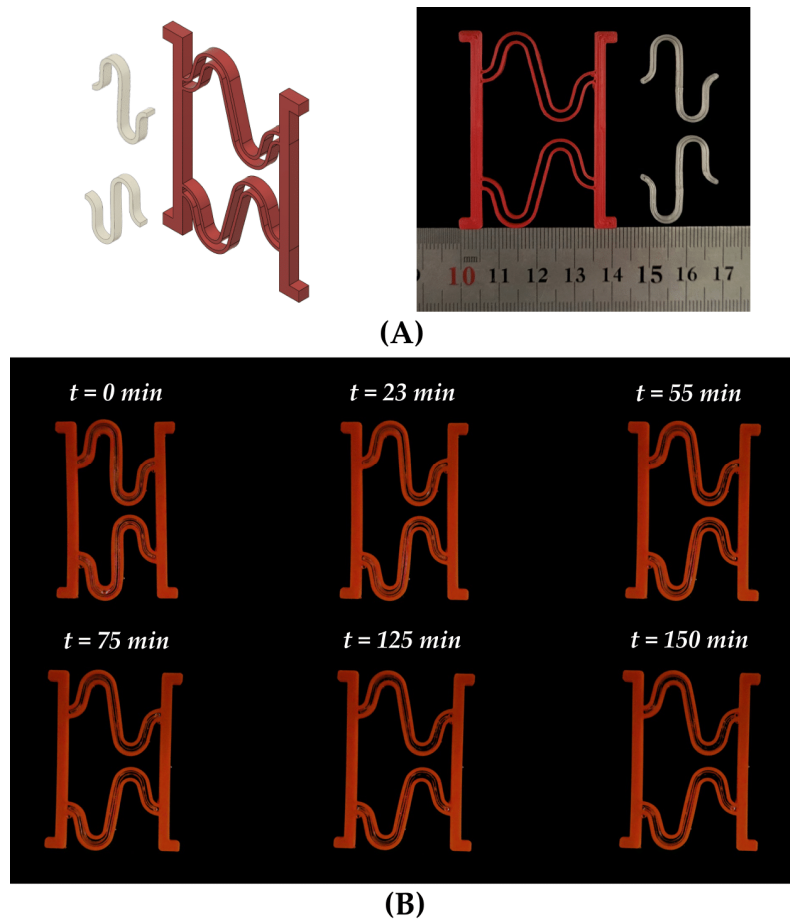


Figure B.36. (A) CAD models & prototypes and (B) shape-morphing test for actuator 36.

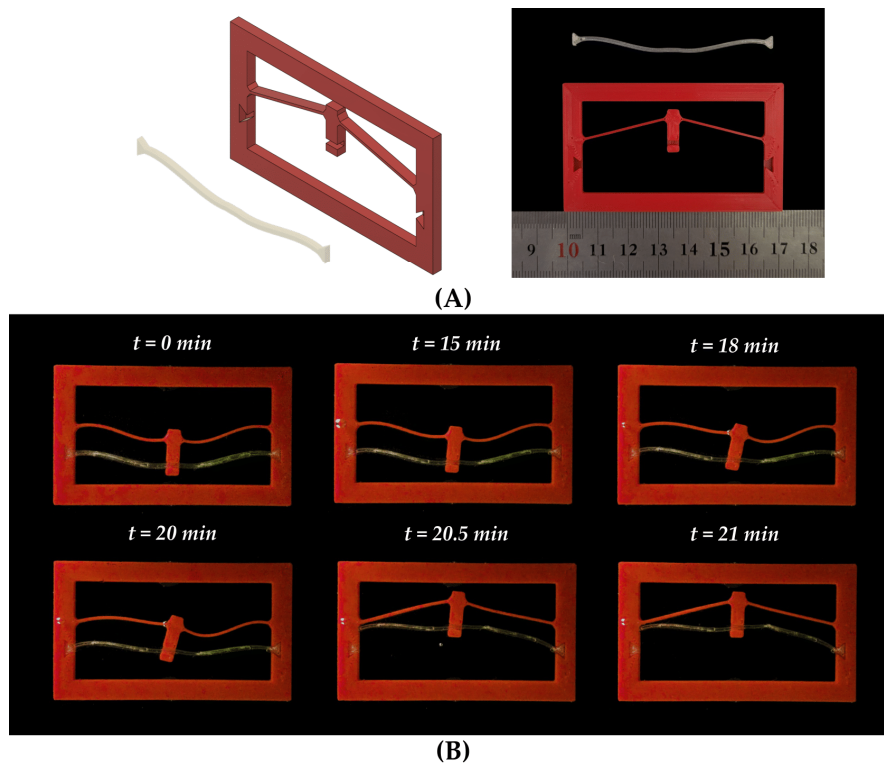


Figure B.37. (A) CAD models & prototypes and (B) shape-morphing test for actuator 37.

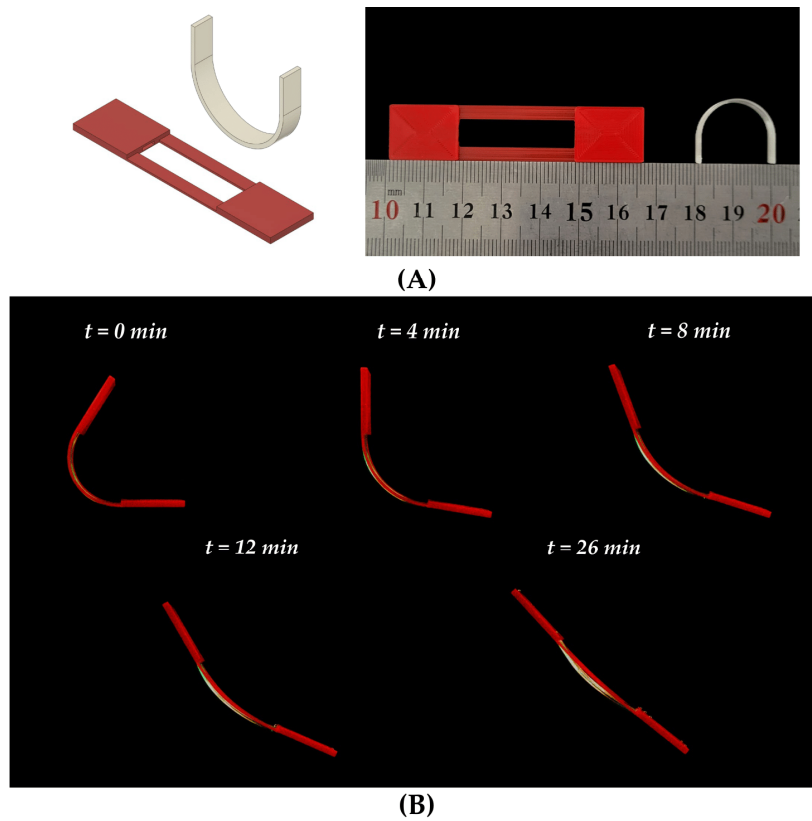


Figure B.38. (A) CAD models & prototypes and (B) shape-morphing test for actuator 38.

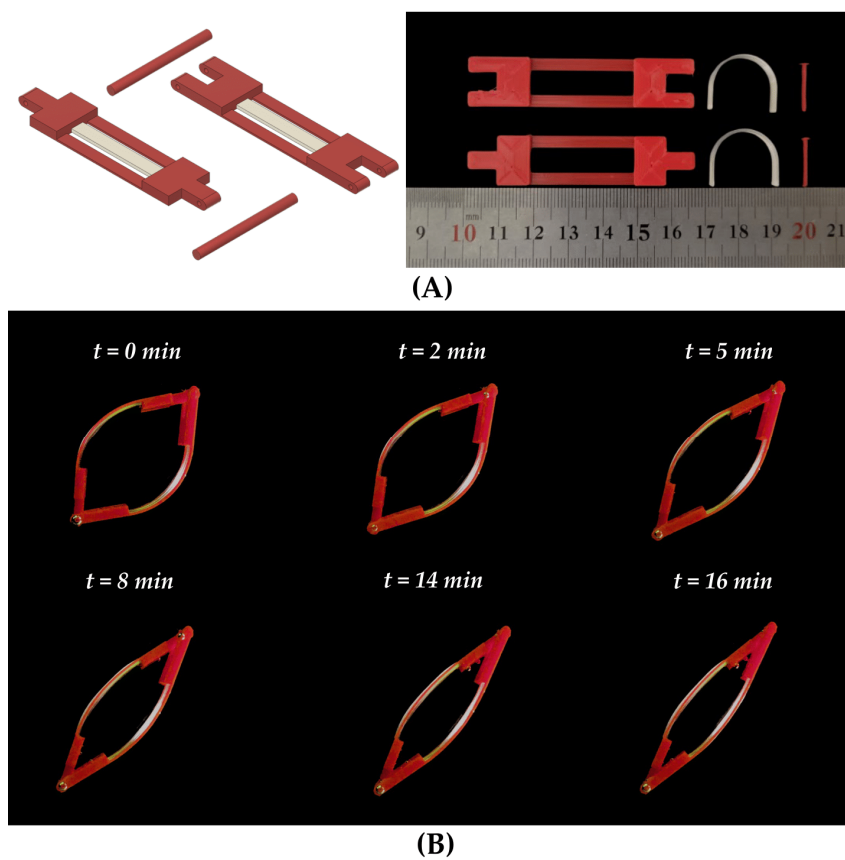


Figure B.39. (A) CAD models & prototypes and (B) shape-morphing test for actuator 39.

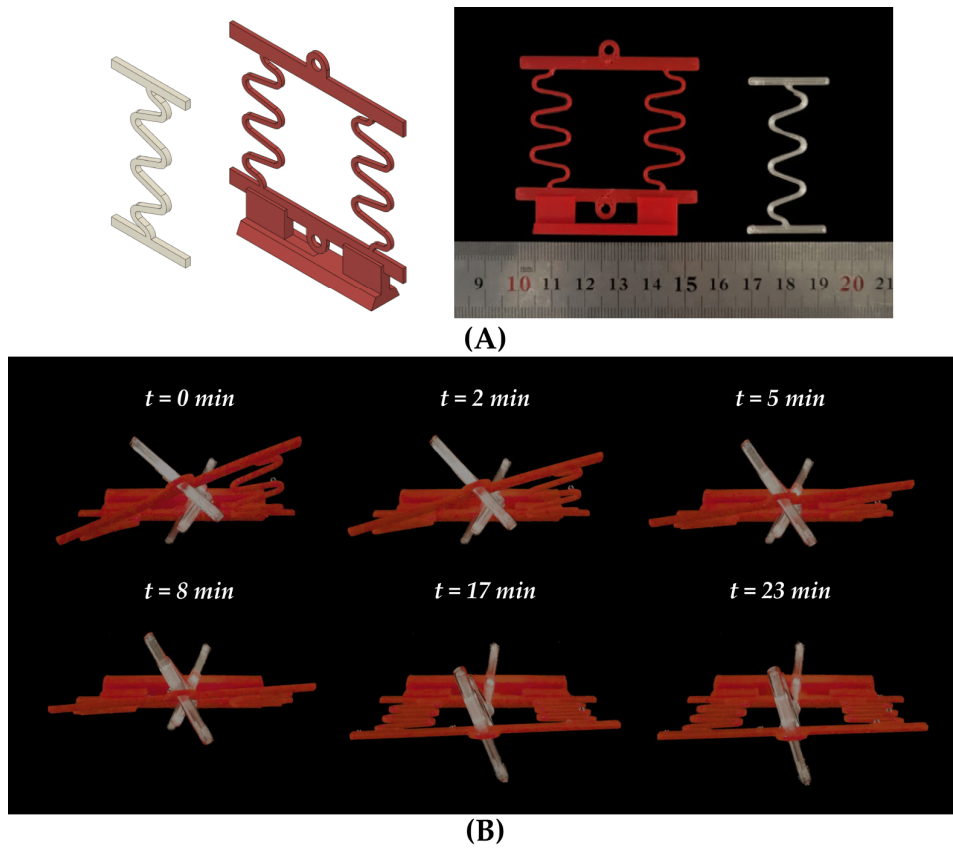


Figure B.40. (A) CAD models & prototypes and (B) shape-morphing test for actuator 40.

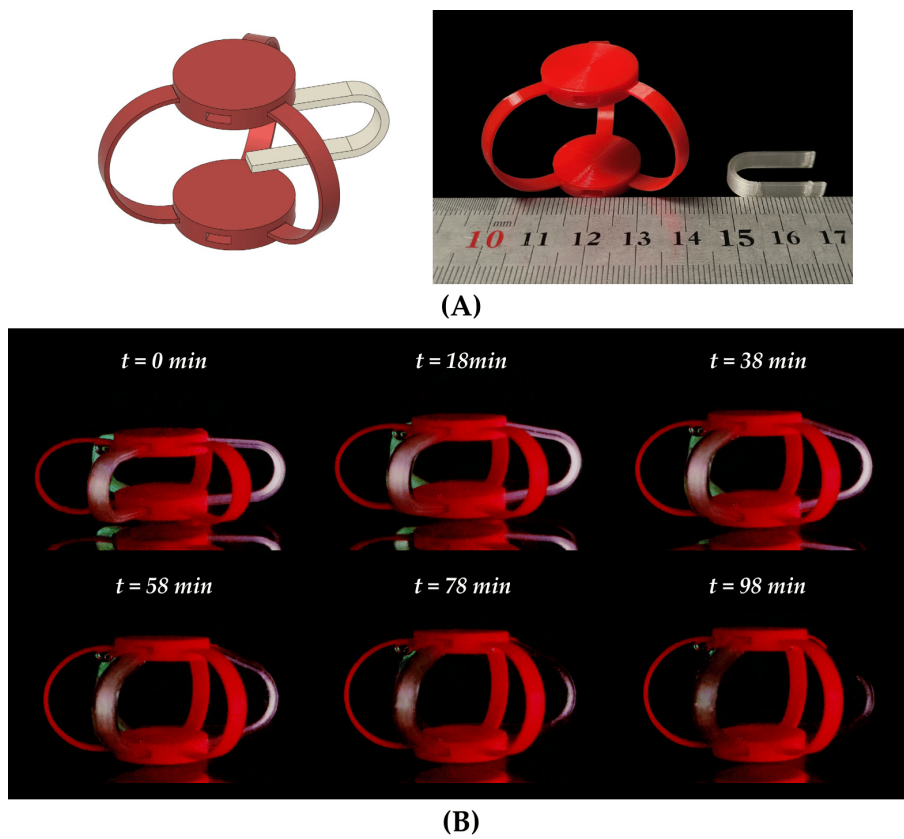


Figure B.41. (A) CAD models & prototypes and (B) shape-morphing test for actuator 41.

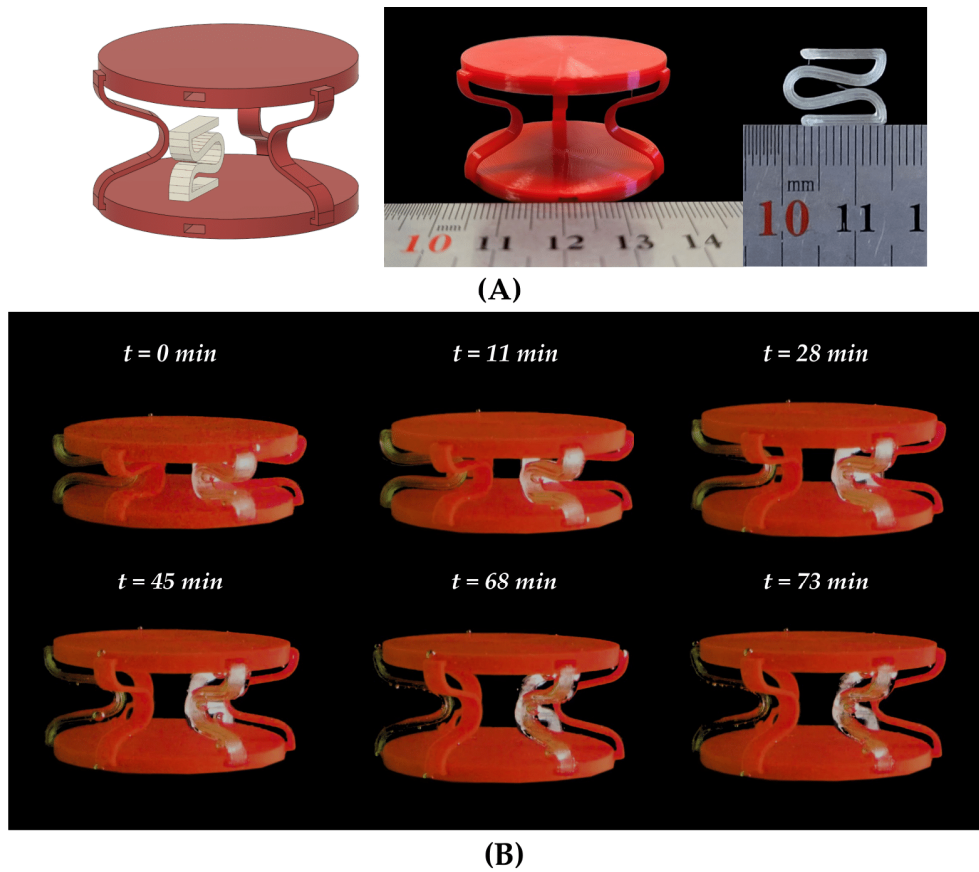


Figure B.42. (A) CAD models & prototypes and (B) shape-morphing test for actuator 42.

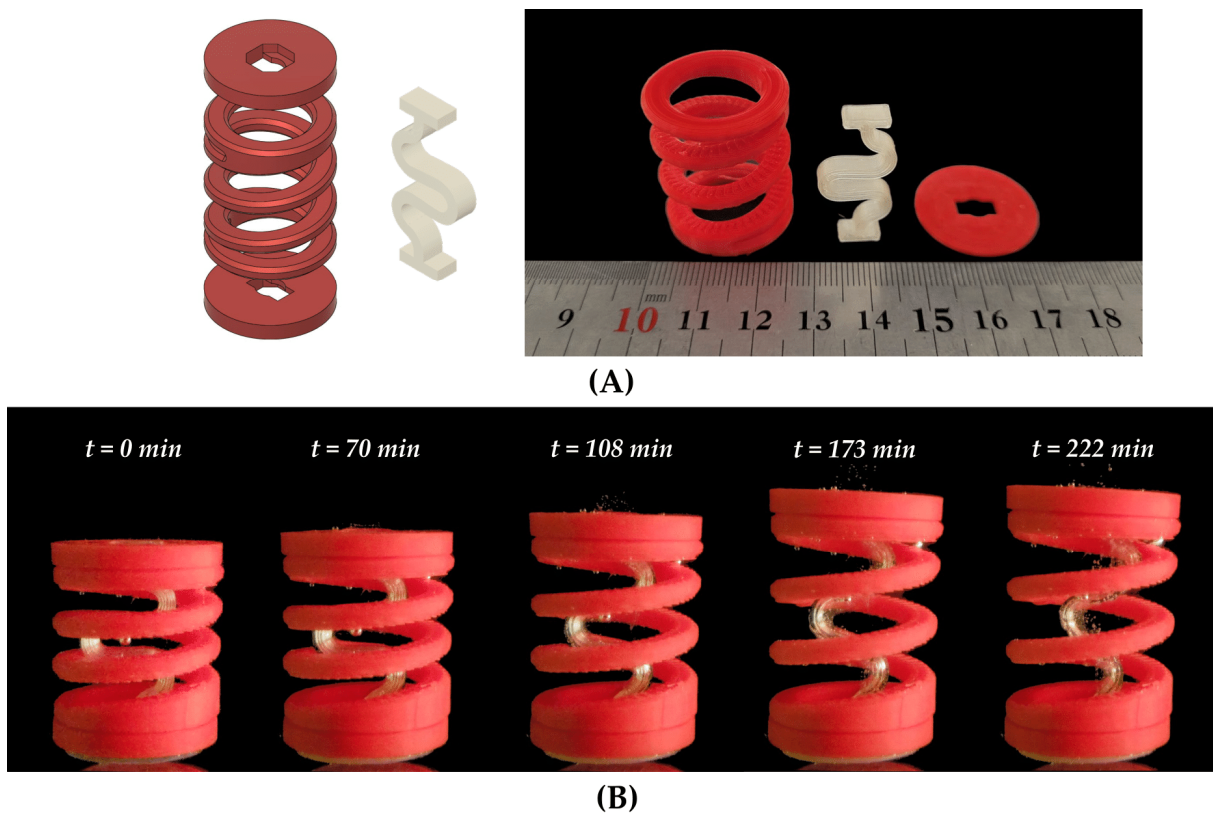


Figure A.43. (A) CAD models & prototypes and (B) shape-morphing test for actuator 43.

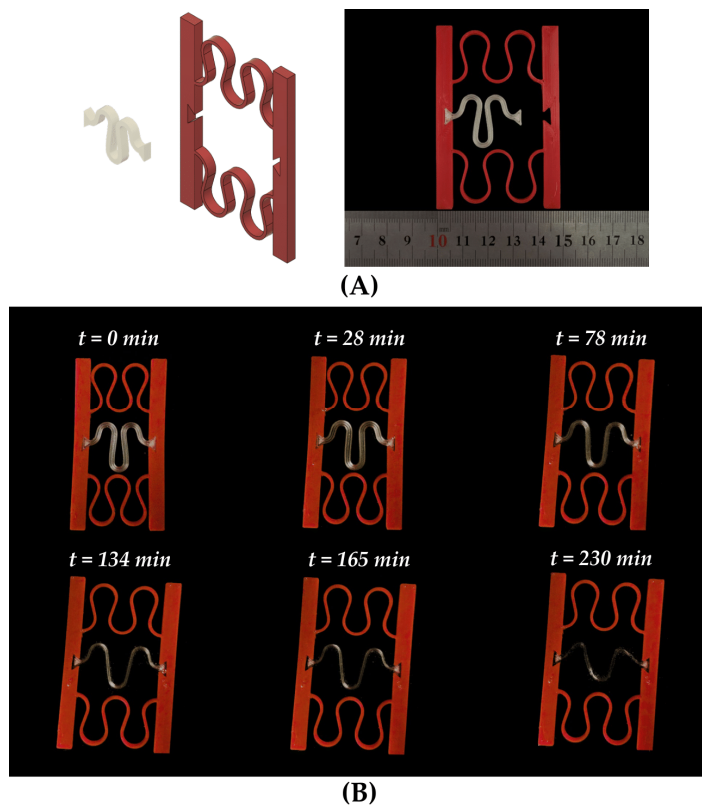


Figure B.44. (A) CAD models & prototypes and (B) shape-morphing test for actuator 44.

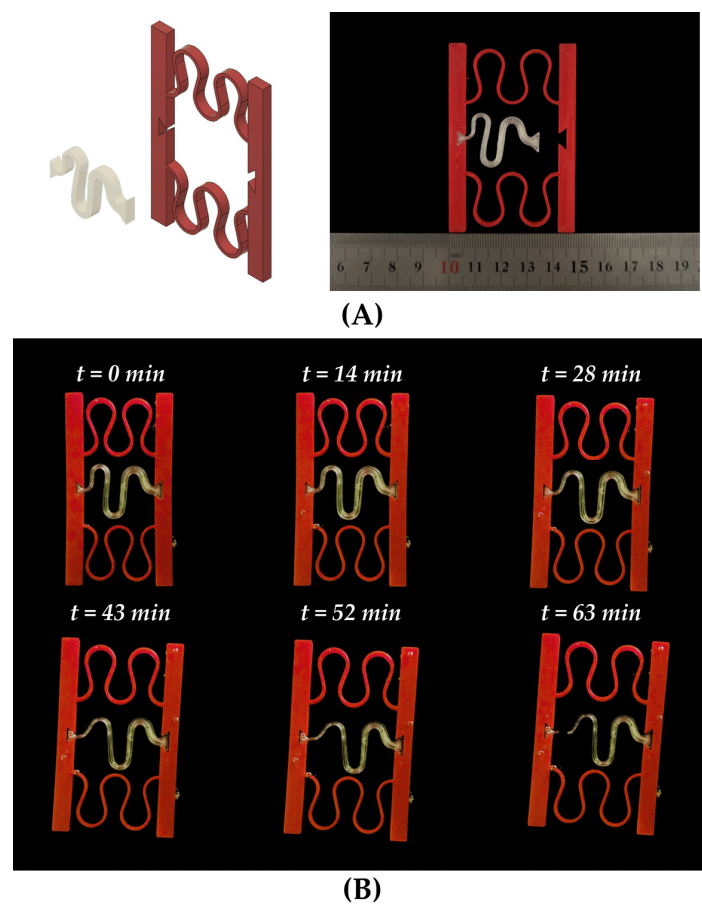


Figure B.45. (A) CAD models & prototypes and (B) shape-morphing test for actuator 45.

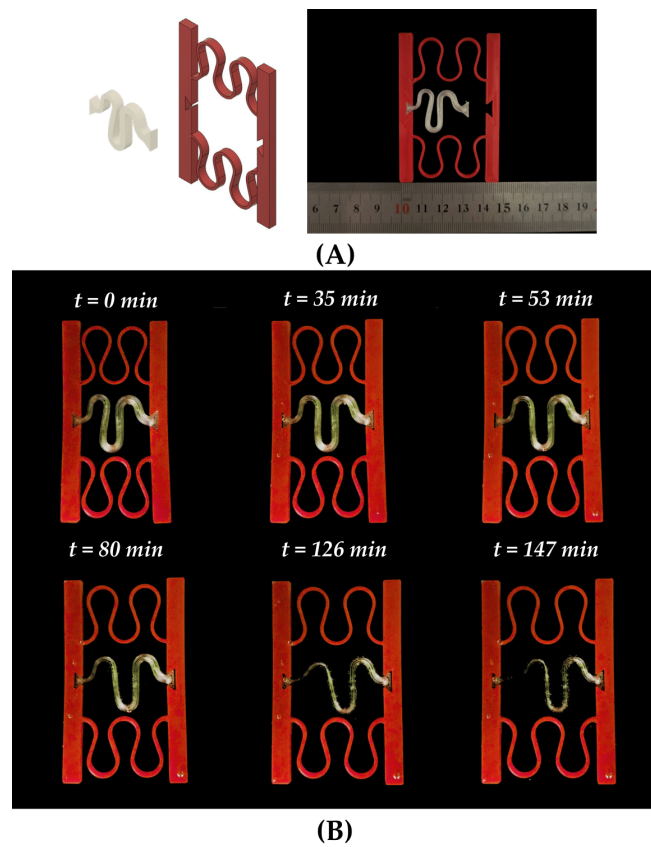


Figure B.46. (A) CAD models & prototypes and (B) shape-morphing test for actuator 46.

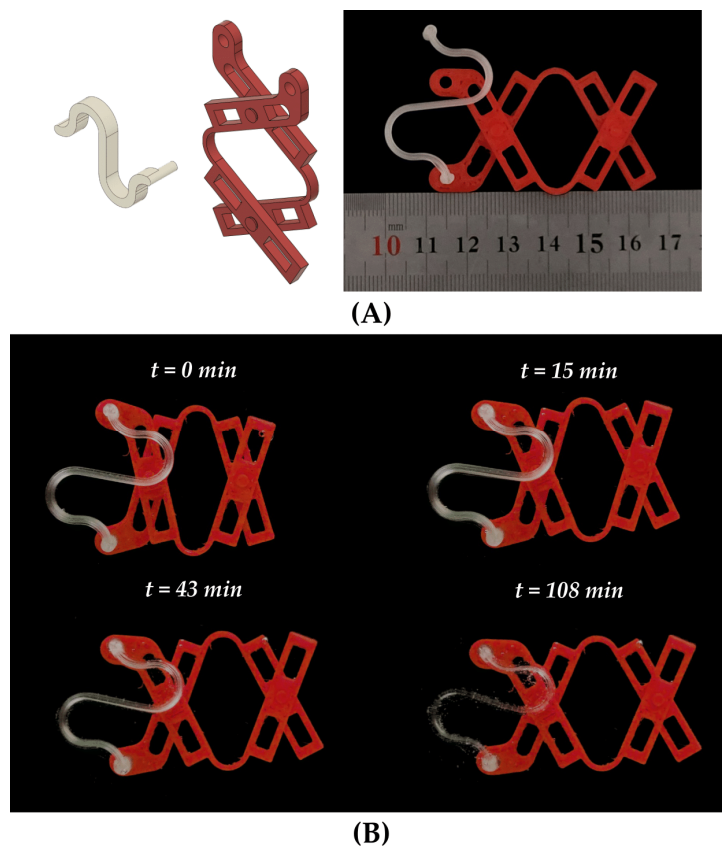


Figure B.47. (A) CAD models & prototypes and (B) shape-morphing test for actuator 47.

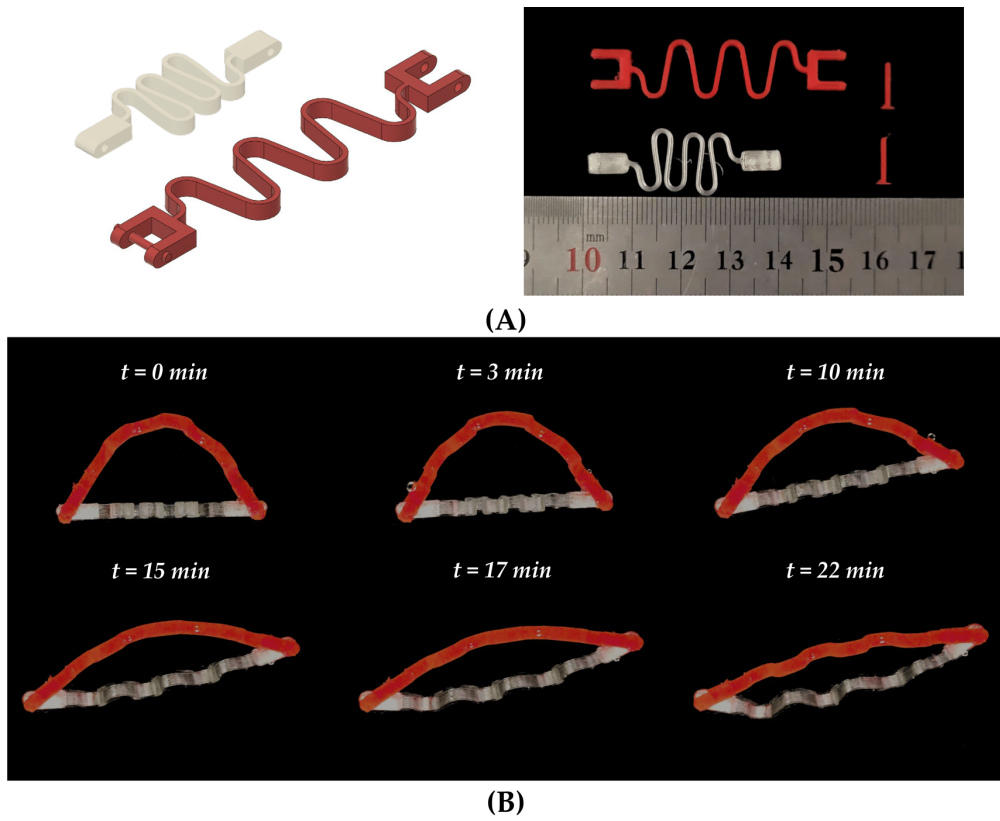


Figure B.48. (A) CAD models & prototypes and (B) shape-morphing test for actuator 48.

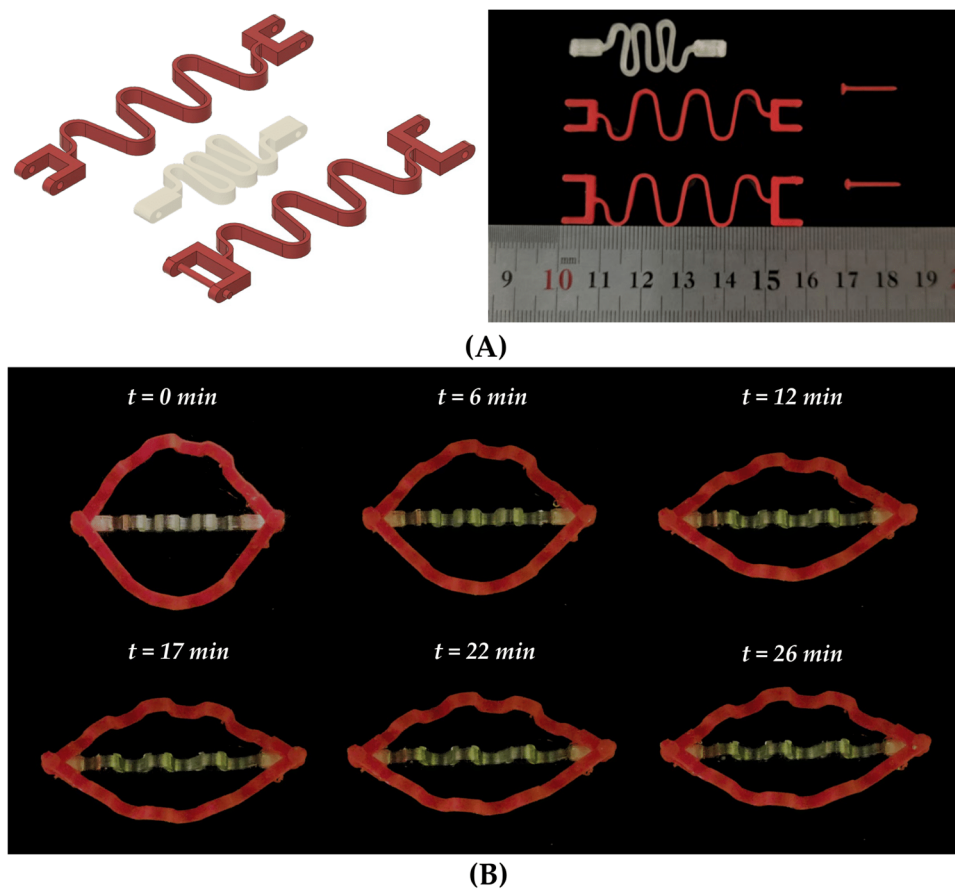


Figure B.49. (A) CAD models & prototypes and (B) shape-morphing test for actuator 49.

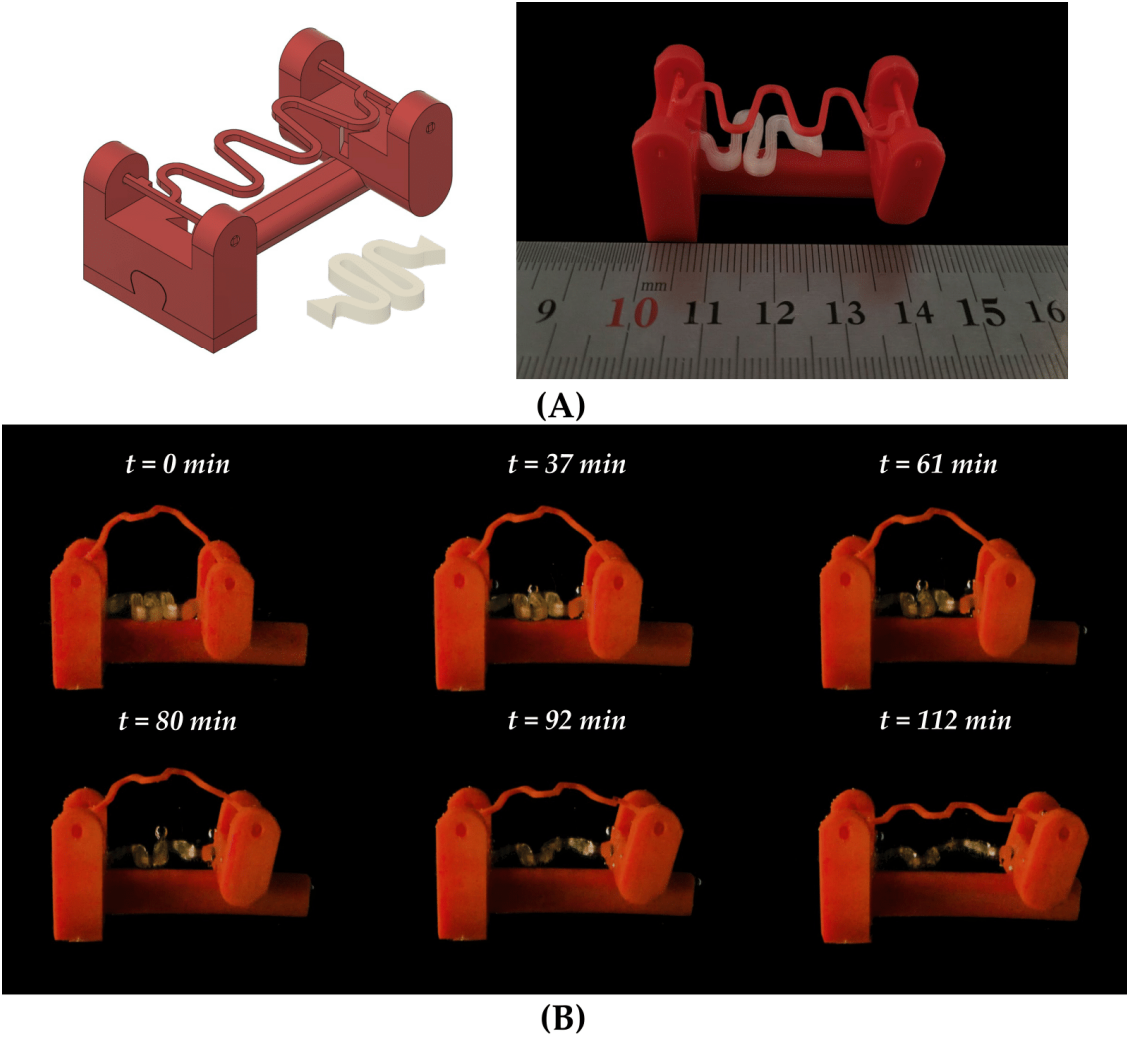


Figure B.50. (A) CAD models & prototypes and (B) shape-morphing test for actuator 50.

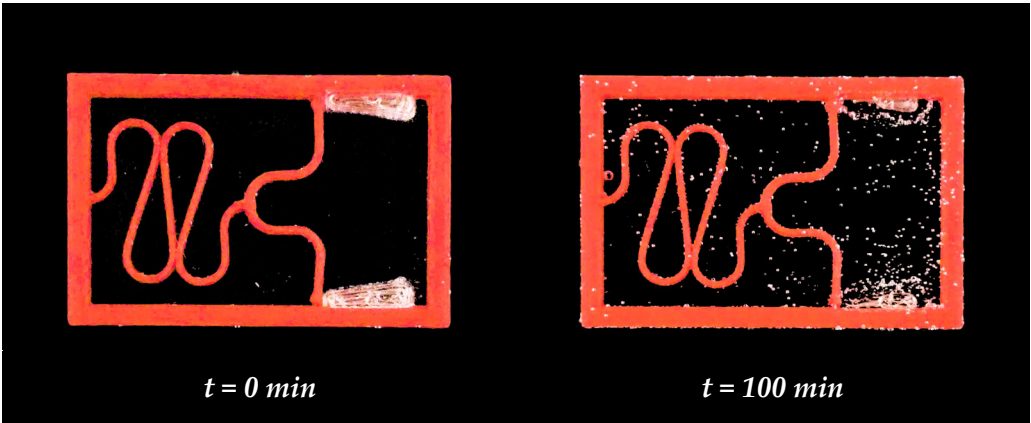


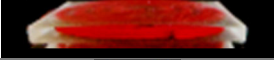
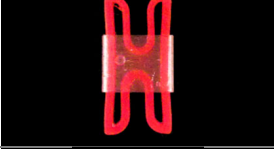


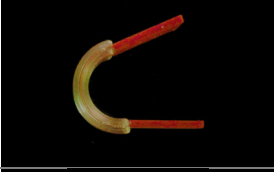
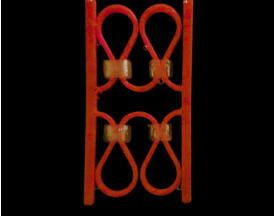


Figure B.51. The first proof of concept tested, the red material made of PLA and the transparent material PVA.

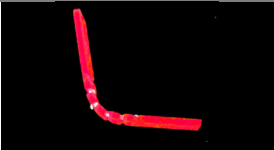


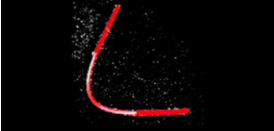




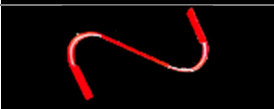



Appendix C. Codification of the collection of shape-morphing actuators










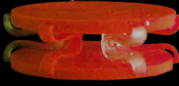


Table A.6. Summary of prototyped and tested shape-morphing actuators with their codification according to ontology for shape-morphing actuators (ontology originally presented in chapter 5, as one of the main outcomes from the creativity promotion action performed leading to a codified description of the actuation life cycle).

Actuator	Representative design image	Geometry	Shape	Shape-morphing principle	Triggering stimuli	Geometry	Shape
1		1D	SSP	STR	DEG	1D	SSP
2		3D	SP	STR	DEG	3D	SP
3		2D	PL	EXP	DEG	3D	D
4		1D	SSP	AUX	DEG	1D	SSP
5		1D	SSP	STR	DEG	1D	SSP
6		2D	STAR-BS	EXP	DEG	2D	STAR-BS
7		2D	V-BS	UF	DEG	1D	B
8		1D	SSP	STR	DEG	1D	SSP

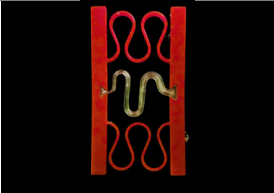
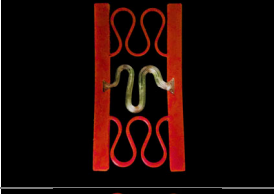
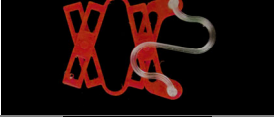


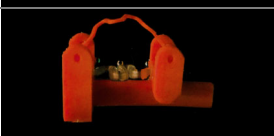
Actuator	Representative design image	Geometry	Shape	Shape-morphing principle	Triggering stimuli	Geometry	Shape
9		1D	SSP	STR	DEG	1D	SSP
10		1D	SSP	STR	DEG	1D	SSP
11		3D	SP	STR	DEG	3D	SP
12		3D	SP	STR	DEG	3D	SP
13		2D	PL	EXP	DEG	3D	D
14		1D	SSP	STR	DEG	1D	SSP
15		1D	SSP	STR	DEG	1D	SSP
16		2D	V-BS	STRA	DEG	2D	U-BS
17		3D	D	COMP	DEG	2D	PL
18		1D	SSP	STR	DEG	1D	SSP
19		1D	SSP	STR	DEG	1D	SSP
20		2D	V-BS	UF	DEG	1D	B

Appendix C. Codification of the collection of shape-morphing actuators

Actuator	Representative design image	Geometry	Shape	Shape-morphing principle	Triggering stimuli	Geometry	Shape
21		2D	V-BS	UF	DEG	1D	B
22		3D	C	O	DEG	2D	PL
23		2D	V-BS	UF	DEG	1D	B
24		2D	V-BS	UF	DEG	1D	B
25		2D	V-BS	UF	DEG	1D	B
26		2D	V-BS	UF	DEG	1D	B
27		3D	V-BS	UF	DEG	2D	PL
28		3D	V-BS	UF	DEG	2D	PL
29		2D	SSP	UF	DEG	1D	B
30		3D	D	O	DEG	2D	PL
31		2D	V-BS	STRA	DEG	2D	U-BS
32		2D	C-BS	STRA	DEG	1D	B

Actuator	Representative design image	Geometry	Shape	Shape-morphing principle	Triggering stimuli	Geometry	Shape
33		1D	B	BS	DEG	1D	B
34		1D	SSP	AUX	DEG	1D	SSP
35		3D	SP	AUX	DEG	3D	SP
36		1D	SSP	STR	DEG	1D	SSP
37		1D	B	BS	DEG	1D	B
38		2D	V-BS	UF	DEG	1D	B
39		2D	O-BS	KU	DEG	2D	I-BS
40		3D	PL	UTW	DEG	2D	PL
41		3D	CY	EXP	DEG	3D	CY
42		3D	CY	AUX	DEG	3D	CY
43		3D	SP	STR	DEG	3D	SP
44		1D	SSP	STR	DEG	1D	SSP

Appendix C. Codification of the collection of shape-morphing actuators

Actuator	Representative design image	Geometry	Shape	Shape-morphing principle	Triggering stimuli	Geometry	Shape
45		1D	SSP	STR	DEG	1D	SSP
46		1D	SSP	STR	DEG	1D	SSP
47		2D	PL	MECHA	DEG	2D	PL
48		2D	U-BS	DBU	DEG	1D	SSP
49		2D	O-BS	DBU	DEG	2D	O-BS
50		2D	U-BS	DBU	DEG	1D	SSP