Received: 24 June 2024 | Revised: 29 August 2024 | Accepted: 10 September 2024

IET Cyber-Systems and Robotics

DOI: 10.1049/csy2.70001

ZHEJIANG UNIVERSITY PRESS | The Institution of Engineering and Technology | WILEY

REVIEW

3D-printed biomimetic and bioinspired soft actuators

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Funding information
Stony Brook University Startup Funds; Washington State University Cougar Cage Funds; Washington State University Startup Funds; National Science Foundation, Grant/Award Number: DGE 2244082; GRFP 2235552; ECCS-2238363

Abstract

A major intent of scientific research is the replication of the behaviour observed in natural spaces. In robotics, these can be through biomimetic movements in devices and inspiration from diverse actions in nature, also known as bioinspired features. An interesting pathway enabling both features is the fabrication of soft actuators. Specifically, 3D-printing has been explored as a potential approach for the development of biomimetic and bioinspired soft actuators. The extent of this method is highlighted through the large array of applications and techniques used to create these devices, as applications from the movement of fern trees to contraction in organs are explored. In this review, different 3D-printing fabrication methods, materials, and types of soft actuators, and their respective applications are discussed in depth. Finally, the extent of their use for present operations and future technological advances are discussed.

KEYWORDS
bio-inspired robotics, piezoelectric actuator (pea)

1 | INTRODUCTION

Biomimicry is an intriguing and flourishing discipline that is rooted in both scientific exploration and engineering ingenuity [1]. It envisions progressive applications in various domains by uncovering adaptive strategies and design principles honed over billions of years of evolutionary refinement. The exploration of these intricate patterns and processes has guided the development of innovative technologies and methodologies that echo the inherent wisdom within living organisms [2].

Biomimicry is the design and creation of materials and systems modelled on natural entities and processes to solve human challenges. Bioinspired and biomimetic designs are a subset of biomimicry. Bioinspired designs are influenced by natural forms and processes without directly mimicking them. Biomimetic designs are intended to imitate the structure, function or processes of biological systems [3].

Historical biomimicry explorations, such as Henry Mitchell's oceanic pile design mimicking seed vessels' burying mechanism and Ader's bat-winged aircraft, have led to efforts to learn from nature's efficient solutions. These extend to modern innovations such as Velcro inspired by burdock seeds and gecko-inspired dry adhesive tape. Despite its modern emergence, humanity's fascination with nature's designs dates back over three millennia, as evidenced by endeavours such as Chinese attempts at artificial silk [4].

Biomimicry and soft robotics have emerged as interconnected fields that hold promise in revolutionising the future of robotics by minimising reliance on electronics [5]. Inspired by nature's elegance, soft robotics seek to design and construct robots using compliant materials, enabling them to interact seamlessly with their environment, adapt to dynamic conditions, and display a higher degree of safety when operating alongside humans [5]. Traditional rigid robots, governed by complex electronic systems, can face limitations in terms of flexibility, mobility, and safety, particularly in delicate or uncertain environments [6]. In contrast, soft robots inspired by natural forms can achieve remarkable dexterity, resilience, and adaptability, relying primarily on materials and mechanical designs that reduce the need for extensive electronic circuitry [7]. Therefore, interest has increased in the development of biomimetic and bioinspired soft robots. The previously mentioned flexible capabilities of such materials can take enormous advantage of perceived movements in nature to manufacture devices that can use such capabilities for their own benefit, either through adapting their movement (biomimicry) or taking inspiration to manufacture unique devices (bioinspired). This shift away from electronics-driven design not only simplifies the manufacturing process but also corresponds with the aspiration to create more environmentally sustainable and biologically inspired robotic systems [8].

The need for movement functionality is a common aspect of performance; soft actuators are used as tools that provide bioinspired soft robot movement. Typically, actuators are instruments in a device that can provide some displacement through force or torque. These are usually controlled through a response, which can be pneumatic, magnetic, shape-memory, etc. Then, the input received is converted into the mechanical energy required to produce movement in the system. In bioinspired applications, soft actuators are preferred due to the flexibility offered by some of these materials and the potential biocompatibility offered by materials such as hydrogels and silicone. However, working with less rigid materials can lead to reproducibility issues even at high resolutions, as well as issues with their integration into devices and interactions with rigid parts. Therefore, the manufacturing of soft actuators for biomimetic and bioinspired applications was initially limited. Nevertheless, the use of emerging technologies, such as 3D-printing, can mitigate some of these disadvantages. Using these techniques, the ability to control the resolution and orientation of some of these soft materials, as they are developed into actuation devices, can significantly improve the feasibility of their use by increasing their manufacturing complexity and speed [9].

3D-printing is a technique developed in the 1980s that uses the addition of a material layer-by-layer to create a three-dimensional shape [10]. As this technology has progressed, it has become more widely available, and the operation costs have dramatically reduced. Its availability has permitted the development of this technology in many different fields, such as aerospace [11], biomedicine [12], and electronics [13]. Owing to its versatility, a large variety of techniques have been developed, some of which allow the use of soft materials. This enables 3D-printing to play a critical role in the development of biomimetic and bioinspired soft robots. The combination of biomimicry and 3D-printing offers potential for bioinspired and biomimetic soft and rigid actuators and robotics. 3D-printing allows for the fabrication of complex and customisable robotic components, primarily via 3D-printed models, as well as the direct printing of components [14]. Moreover, the biomimetic approach ensures that the mechanical properties and geometries of these structures align with the functions they need to perform, optimising their effectiveness [15].

Materials such as hydrogels and silicone can be cast in 3D-printed moulds or 3D printed directly. 3D-printing can provide a larger array of shapes and functionalities, as well as extend the variety of materials that can be used, such as shape memory polymers (SMPs) and elastomers. The combination of these factors has led to aid in many sectors, such as biomedical space, with actuating motions used to replicate muscle, lung and heart compressions and expansions. As soft actuators are refined, they are expected to play a key role in the development of biomedical organ models (e.g. presurgical rehearsal) in the future. Similarly, the incorporation of human responsiveness and action is an area of great interest in soft robotics. The use of 3D/4D-printing technologies in combination with these soft materials can enable the fabrication of different functionalities, such as sensing or gripping [16–19]. An example of recent gripping and sensing technology used in this work by Han et al. involves the use of a conductive polymer in the form of thermoplastic polyurethane (TPU) along with the incorporation of metal wires with polymer nanocomposites using a multiprinting technique. Sensing grippers were fabricated that can detect compression levels and adjustable gripping through Joule heating, using a conductive polylactic acid (PLA) base to adjust joint stiffness and create movement [18]. The versatility of 3D-printing techniques extends the array of soft actuators that can be fabricated through biomimicry.

Significant technological advancements can be achieved through imitating and drawing ideas from natural phenomena and behaviours. Therefore, it is crucial to continue developing and improving systems that replicate and are inspired by nature. This has created interest in discussing and discovering the extent of 3D/4D-printing technologies. The advances observed in the development of 3D/4D-printed devices have been previously discussed with respect to the use of 3D-printing to incorporate soft polymeric materials for intelligent actuation [20, 21], the different materials used to create these 3D/4D devices and their use [22], and their manufacturing processes and actuation of bioinspired soft robots [23, 24]. Importantly, Zhang et al. expanded on the rising technologies to develop these soft actuators, as well as their potential applications [23]. One of the main limitations of this technology is the precise control of movement within a 3D plane. The use of 3D/4D printing can potentially aid in limiting this, as mentioned by Khalid et al., where many potential uses of 3D/4D printing can limit some of the hinderances observed [24]. This review focuses on the different manufacturing techniques for biomimetic and bioinspired 3D/4D devices, as well as the various actuation devices used to permit movement in soft robots and some of the applications that have motivated research in these areas, especially those observed in both the human body and other living organisms, such as plants and animals. An overview of these items is presented in Figure 1. The current state of these methods as well as their outlook will also be discussed.

2 | MATERIALS AND FABRICATION

Soft actuators leverage materials, such as hydrogels, polymers, and silicone-based compounds, with 3D/4D printing improving design precision and functionality (e.g. hydrogels for natural movement replication and EcoFLEX for biomedical applications). Advanced 3D-printing techniques, such as direct ink writing (DIW), PolyJet, stereolithography (SLA), Digital Layer Processing (DLP), and fused deposition modelling (FDM), enable the creation of complex precise structures, supporting bioinspired designs and rapid prototyping in soft robotics.

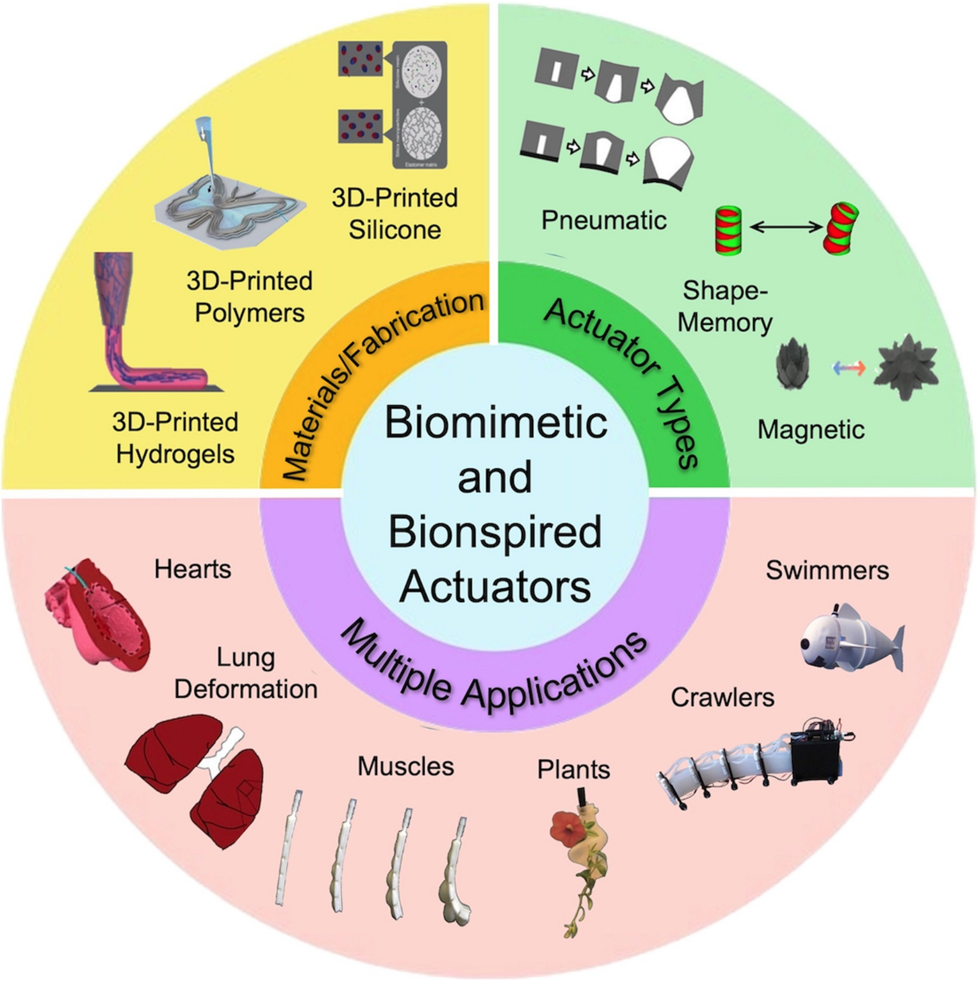

FIGURE 1 Overview schematic of materials, 3D-printing fabrication, types and applications observed within biomimetic and bioinspired soft actuators. Reproduced from refs. [25–35].

2.1 | Materials for soft actuators and devices

A large variety of materials are used to create soft actuators, including hydrogels [36], polymers [37], and silicone-based materials [38], among others. Historically, these materials have also been 3D-printed to enhance their structural design capabilities for bioinspired actuation. The flexibility of these soft actuators is highly influential for biomimetic applications. However, the use of these soft materials has several disadvantages, as some can be considered difficult to print, and it is difficult to achieve precise features, especially at lower scales [39]. Nevertheless, the mentioned flexibility makes them capable materials for the development of such devices. The materials, advantages, and disadvantages are listed in Table 1. In this section, several of the major substances used in the fabrication of soft actuators and devices are discussed.

2.1.1 | Hydrogels

Hydrogels are polymer chains that are highly hydrophilic, as they absorb enormous amounts of water, enabling them to swell. This property facilitates their use in soft material applications, as they can replicate many of the material properties observed in nature. Similarly, the use of hydrogels has been extensively studied due to their high biocompatibility and low Young's modulus. Its flexibility can potentially establish its ability to replicate different movements and functions in nature, such as the use of myocadiac contraction and relaxation using a thin hydrogel layer, which is based on gelatine [40]. Temperature-responsive hydrogels have emerged as functional materials for programmable motions. For instance, Gladman et al. mimicked the structural composition of plant cell walls [25], where a hydrogel composed of rigid cellulose fibrils embedded within a soft acrylamide matrix was developed (Figure 2a).

2.1.2 | Soft silicone

Soft silicone rubbers such as EcoFlex and Dragon Skin are widely popular materials in the field of soft robotics due to their unique properties and versatility [41]. These materials belong to the family of silicone elastomers, which exhibit

TABLE 1 Fabrication methods in soft robotics.

Method	Description	Advantage	Disadvantage	Material	Application
DIW	Customised 3D printers using soft materials such as hydrogels and silicone-based mixtures for fabricating soft robots.	Flexibility in accommodating various materials and printing processes; precise control over printing parameters and magnetisation profiles.	Limited in manufacturing complex 3D structures compared to other methods.	Hydrogels, silicone-based mixtures, polymer composite with magnetised NdFeB	Fabrication of magnetic soft actuators, customised soft robots
PolyJet	Deposits photopolymer in a building bed and cures it immediately with UV light; high-speed and precise printing of complex shapes.	Precise, high-quality, and fast; integrates sensing and actuating components in multi-material 3D-printing.	Concerns regarding delamination and its impact on actuation performance.	Soft/thermoplastic resins	Manufacturing complex shapes for bioinspired actuators, integration with soft sensors
SLA	Uses a laser to selectively cure liquid photopolymer resin, creating accurate and detailed 3D objects with smooth surface finishes.	High precision and detail; ideal for biomimicry applications and creating intricate biomimetic prototypes.	Limited to photopolymer resins; can be more expensive and slower than other methods.	Photopolymer resins	Biomimicry applications, mould making, direct printing of actuators
DLP	Uses a projected light to crosslink photopolymer resin, allowing for high-resolution prints with soft elastomeric resins.	High resolution; programmable 3D magnetisation profiles; favourable for manufacturing soft robots and actuators.	Limited print thickness due to incorporation of magnetic particles making the UV resin opaque.	Soft elastomeric resins, photopolymer resins	Manufacturing soft robots, multi-legged paddle crawler robots
FDM	Extrudes thermoplastics layer by layer to form 3D structures; common in 3D-printing with materials like PLA and ABS that often blended with softer materials for actuators.	Widely accessible and popular; allows for multi-printing with different functionalities such as grippers with sensors, and extensively used for creating moulds for soft actuators.	Limited availability of highly flexible filaments; usually used for moulds and minor components rather than main structures.	PLA, ABS, PVDF	Creation of moulds for soft actuators, minor components with incorporated sensors
Mould processes	Involves designing and 3D-printing moulds, typically using hard polymers; moulds are used to cast soft silicone materials to create soft robotic structures.	Versatile and precise; rapid prototyping and iterative design improvements; cost-effective compared to traditional mould-making techniques.	Requires additional steps for casting and curing; limited to mould-making rather than direct fabrication of components.	PLA, ABS, silicone, hydrogels	Development of soft robots with complex and bioinspired features, casting of soft silicone components

Abbreviations: ABS, acrylonitrile butadiene styrene; DIW, direct ink writing; DLP, digital light processing; FDM, fused deposition modelling; NdFeB, neodymium–iron–boron; PLA, polylactic acid; PVDF, polyvinylidene fluoride; SLA, stereolithography.

exceptional elasticity, flexibility, and resilience. Soft silicone rubbers are incredibly pliable and able to deform easily under external forces. They also possess high tear strength and good resistance to wear, ensuring longevity in applications that involve repeated mechanical stress [42].

One key property that sets soft silicone rubbers apart is their viscoelastic behaviour. They display both viscous (liquid-like) and elastic (solid-like) characteristics, allowing for energy absorption and dissipation during deformations [43]. This feature makes them ideal for soft robotics and devices, where compliant and adaptive materials are necessary to mimic the movements and responses of living organisms. Their biocompatibility and non-toxicity to the skin make them suitable for biomedical applications, such as wearable devices [43] or assistive robotics for rehabilitation purposes. Furthermore, their viscoelastic nature facilitates energy-efficient movements and provides robustness against sudden impacts or changes in the environment [44].

2.1.3 | Other polymers

In general, polymers have a large variety of properties and features, meaning that they can cover many different applications. For soft actuators, polyvinyl alcohol (PVA) and polyvinylidene fluoride (PVDF) are useful in the development of shape-morphing devices. Zhang et al. demonstrated that PVDF, a common soft polymer in many technologies, underwent curling and recovered its shape through hydration [45]. These polymer-based actuators were developed through the combination of thermoresponsive PVDF and the thermo/hydroresponsive element PVA, which can perform curling due to the contrasting responses.

Thermoplastic acrylonitrile butadiene styrene (ABS) and PLA exhibit durability and impact resistance. These features make ABS and PLA suitable for 3D-printed moulds. Thus, they are highly useful in bioinspired and biomimetic designs

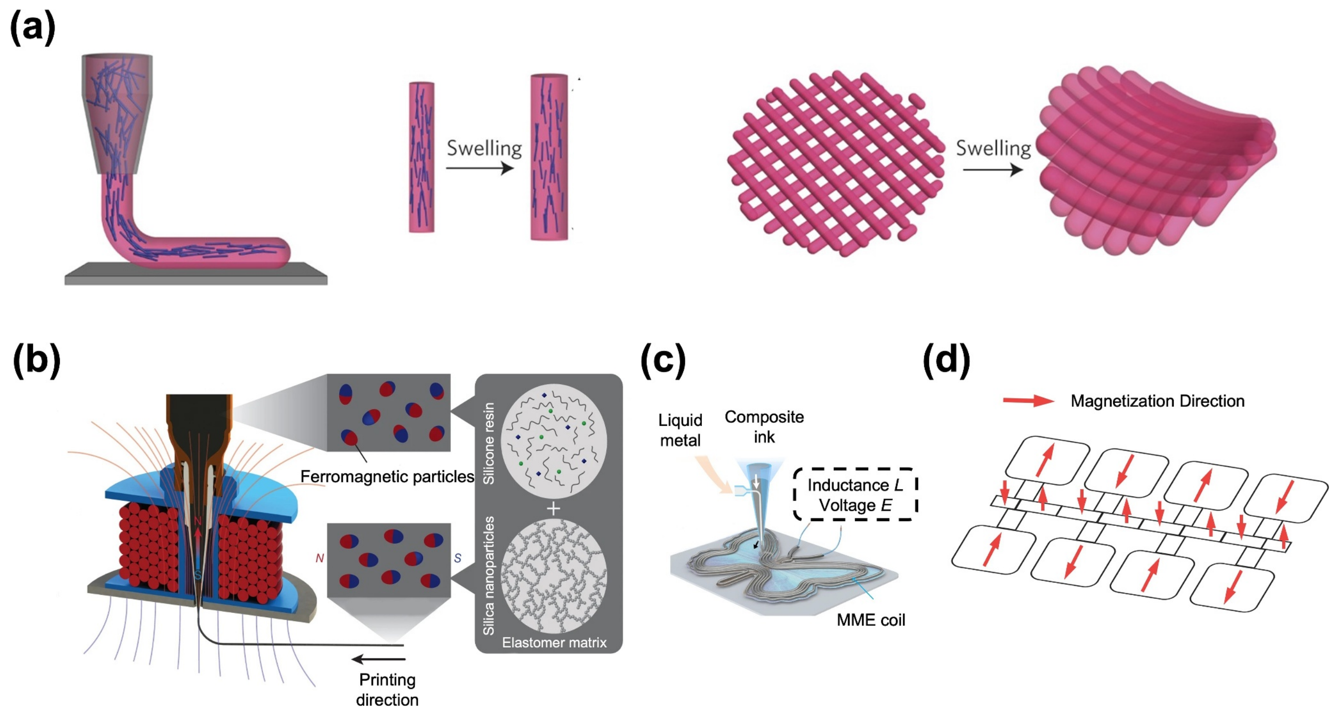

FIGURE 2 3D-printed actuators fabricated using soft materials. (a) Schematic of the shear-induced alignment of cellulose fibrils and a 3D-printed flower, demonstrating a range of morphologies inspired by a native orchid. Reproduced from Ref. [25]. (b) Examples of printed magnetic and SMP-based soft actuators. Reproduced from ref. [26]. (c) Schematics of coaxial printing of a bionic magnetic soft actuator with self-sensing capability. Reproduced from ref. [27]. (d) DLP-printed multi-legged paddle crawler robots with a 3D magnetisation profile. SMP, shape memory polymer, DLP, MME.

[37]. Both methods are heavily utilised in conventional 3D-printing techniques such as FDM.

Polyethylene terephthalate (PET) is a thermoplastic that is most notably found in packaging such as water bottles [46]. PET is lightweight, durable, and flexible. TPU is also flexible but significantly less flexible than silicone rubber [47]. PET is typically formed in sheets, and TPU can be formed into filaments for use in 3D printing. The use of flexible materials is vital for the manufacture of potential soft actuators, making these thermoplastics important.

Resins are commonly used in SLA and direct laser printing, which require photopolymerisation to cure these materials. For soft robotics, the inclusion of elastic polymers is necessary, as they can provide flexibility that other polymer materials cannot achieve after crosslinking. A method that can be used to tune the elastic moduli is to control the degree of crosslinking by varying the ratio of polymer to crosslinker in the feedstock. Borello et al. used ethylene glycol phenyl ether acetate (EGPEA) to obtain a variation in elastic modulus from 0.6 to 31 MPa by tuning the previously mentioned ratios of polymer and crosslinker [48]. The ability to tune the mechanical properties as well as the high quality presented by stereolithographic techniques makes resins suitable candidates for manufacturing soft actuators.

Ionic polymer metal composites (IPMCs) represent a class of electroactive polymers comprising an ion-exchange membrane sandwiched between electrode layers. When it is immersed in an electrolyte solution and/or when a voltage is applied to its electrodes, an IPMC deforms due to ion migration and redistribution [49, 50].

2.2 | 3D/4D-printing fabrication

3D/4D printing is used as the main method to fabricate delicate structures for biomimetic/bioinspired actuators in soft robots. The use of 3D/4D printing to obtain more precise structures has been pursued, as seen in work by Schaffner et al., silicone materials were 3D/4D printed while presenting tunable elasticities that can replicate certain precise movements such as the extension of an elephant's trunk, using DIW to manufacture these devices [51]. Bioinspired and biomimetic actuation is not limited to certain materials; however, flexibility and tunability are preferred for more precise manipulation. The following methods, as well as some of their advantages, preferred material selection, and disadvantages, are discussed in Table 1.

2.2.1 | 3D/4D-printed devices with DIW

Customised 3D printers are a significant advancement in additive manufacturing technology. These DIW printers are designed and tailored to meet specific requirements and applications, offering unique capabilities beyond standard off-the-shelf models. Here, soft materials such as hydrogels and silicone-based mixtures are generally used, making them favourable for fabricating soft robots. One of the key advantages of customised 3D printers is their flexibility in accommodating various customised materials and printing processes. Researchers can optimise the printer's hardware, software, and firmware to suit their specific needs, enabling precise control over printing parameters and enhancing overall printing performance. For example, conventional fabrication methods, such as moulding and casting, are limited in their ability to precisely control the magnetisation profile and manufacture complex 3D/4D structures [52]. Kim et al. pioneered the fabrication of magnetic soft actuators using DIW, as shown in Figure 2b [26]. The ink was made by dispersing magnetised neodymium–iron–boron (NdFeB) in composites of silicone. The precise control of the magnetisation profile was achieved by a weak magnetic field around the nozzle tip from an electromagnet or a permanent magnet during printing.

2.2.2 | 3D/4D-printed actuators with polyjet

Polyjet is a 3D-printing technique that deposits a photopolymer in a building bed and cures it immediately with ultraviolet (UV) light. It is a precise, high-quality technique that operates at high speed without requiring a post-curing process. Generally, a large array of resins with different viscoelastic properties can be used in polyjet. For soft robotic applications, soft/thermoplastic resins are preferred. In the printing process, many droplets of the photopolymer are deposited at the same time, while UV light cures each layer. This enables the manufacturing of very complex shapes, which can be used when bioinspired actuators are being fabricated [53]. While recent advancements in soft sensors hold promise for integration with magnetic soft robots to provide feedback, concerns regarding delamination and its impact on actuation performance persist [27, 54]. To address these concerns, multimaterial 3D/4D printing (such as polyjet) of magnetic soft actuators enables the integration of sensing and actuating components, as shown in Figure 2c [27].

2.2.3 | 3D/4D-printed actuators with SLA

SLA is an additive manufacturing technique that uses a laser to selectively cure liquid photopolymer resin, creating accurate and detailed 3D objects with smooth surface finishes [55]. Its ability to fabricate complex and precise structures makes it highly valuable for biomimicry applications (both in mould making and direct printing of actuators), enabling researchers and designers to mimic natural forms and structures found in living organisms with remarkable accuracy. The ability of SLA to produce intricate biomimetic prototypes and components facilitates the exploration and implementation of nature-inspired design solutions.

2.2.4 | 3D/4D-printed actuators with DLP

In a way comparable to SLA, DLP uses projected light to crosslink the photopolymer resin being printed, which enables the presence of high-resolution prints. The main difference between the two techniques is the application of UV curing: SLA employs this method on a layer-by-layer basis, whereas DLP applies a patterned mask in which the UV light is cured but still follows the same concept as SLA. Due to the high resolution and potential ability to incorporate soft elastomeric resins, DLP has been favoured in the manufacturing of some soft robots and actuators. A programmable 3D magnetisation profile approach was achieved with DLP [56, 57] by the fabrication of a multi-legged paddle crawler robot (Figure 2d) [57], which demonstrated higher motion precision and accuracy. However, DLP printing is limited in terms of print thickness due to the incorporation of magnetic particles that make the UV resin opaque [54, 57].

2.2.5 | 3D/4D-printed actuators with FDM

Additive manufacturing techniques such as DIW, SLA, and FDM enable the creation of 3D/4D objects through layer-by-layer construction. FDM is conventionally associated with 3D printing and has gained popularity as a widely accessible additive manufacturing technique. FDM, specifically, involves extruding thermoplastics to form 3D structures. In the most well-known method, the material, a filament wound onto a roll, is pulled by a drive wheel and fed into a temperature-controlled nozzle head, where it is heated to a semiliquid state. The nozzle extrudes the material in ultrathin layers, following the contours specified by the programme, typically CAD, within the FDM work system [58]. Here, the most common materials used are PLA and ABS. However, due to their rigidity, they are usually blended with a softer, more flexible material, such as PVDF, to produce actuating devices with potential biomimetic or bioinspired movement. Similarly, the use of multi-printing through FDM processes has demonstrated the ability to manufacture actuators with different functionalities, such as grippers with incorporated sensors [18]. Other methods of extrusion exist, such as plunger- or screw-based methods. The limited availability of highly flexible filaments restricts the use of FDM in 3D-printed moulds and minor components [59]. However, despite this limitation, FDM is extensively used for creating moulds for soft actuators, making it a valuable method in the field of soft robotics.

2.2.6 | 3D-printed actuators with mould processes

A typical mould-making process for soft silicone in soft robotics often involves the use of 3D-printed moulds due to their versatility and precision. The process begins with the design and 3D-printing of the mould. The mould is modelled in a 3D modelling software and then 3D printed, often with a commercial 3D printer utilising hard polymers such as PLA or ABS. This step allows for rapid prototyping and iterative design improvements, which are essential in the development of soft robots with complex and bioinspired features. Once the 3D-printed mould is ready, it is then used to cast the soft silicone material. The polymers (including silicone and hydrogels) are poured into the mould, and a controlled curing process ensures that the material takes the shape of the mould and solidifies into the desired soft robotic structure. After curing, the silicone is carefully removed from the mould, resulting in a functional and biomimetic soft robotic component [60]. Compared with traditional mould-making techniques, the use of 3D-printed moulds in soft robotics offers numerous advantages, such as reduced lead times, increased design flexibility, and cost-effectiveness [61]. However, advances in 3D-printing technologies have made mould processes significantly less viable, as they are not able to offer some of the intricate features that 3D/4D-printing techniques are able to achieve with the same accuracy, rendering these processes less complex. Similarly, while the use of mould processes has been important for the growth of soft robots, it is currently not preferred in the use of 3D/4D devices because of these limitations. However, this process's popularity and simplicity still attract usage in the development of soft actuators.

3 | TYPES OF BIOMIMETIC/BIOINSPIRED ACTUATORS

The manufacturing of biomimetic and bioinspired devices predominantly involves the use of actuators because of their ability to facilitate multidirectional movements in soft robots. These actuators can be produced using various responsive elements that induce deformation and contraction. Due to the versatility of movements observed in nature, many types of actuators can be created and applied to various needs (i.e. locomotion). In this section, different actuator types used for bioinspired and biomimetic applications are discussed. Many devices and their usage in different applications are also expanded in Table 2.

3.1 | Magnetic actuators

Magnetic soft actuators, which utilise polymers dispersed with various magnetic fillers, such as NdFeB particles, iron oxide particles, iron particles, and nickel particles, are promising approaches for biomimetic or bioinspired soft actuators [62]. These magnetic composites respond to external magnetic fields, either from electromagnets or permanent magnets, by aligning themselves with the field. This induces deformation in soft actuators through magnetic forces or torques [54, 63]. The magnetisation profile of these actuators plays a pivotal role in their morphological transformations. The magnetic profiles determine the direction and magnitude of the exerted magnetic forces or torques in response to specific external magnetic fields [64].

One method used in the fabrication of magnetic actuators is DLP. As shown in Figure 3a, magnetic particles can be embedded in photopolymers with elastic properties to facilitate the development of soft actuators with magnetic properties [54]. Similarly, the FDM can be used to produce magnetic actuators, usually via a two-step process. The addition of these magnetic particles into the filament structures has a similar effect as that observed in DLP. Then, magnetic actuators can be transformed into intricate biomimetic 3D/4D structures, such as grippers, flowers, and butterflies, as illustrated in Figure 3b [28].

3.2 | Shape memory actuators

SMPs are polymers with intrinsic shape programming capabilities, enabling materials to become actuators [66]. This shape programming process, consisting of shape deformation, shape fixation, and stress release, determines the pathway of polymer transformation [66, 67]. SMPs can be categorised into one-way SMPs and two-way SMPs [57].

One-way SMPs undergo irreversible shape alteration, retaining a permanent form after reverting from a temporary configuration until they are subjected to deformation again [62, 66, 67]. Fundamentals to one-way SMPs are netpoints that define the permanent shape, and switchable segments which are responsible for temporary shape manipulation [66]. FDM, a widely used and low-cost printing technology, has been adapted for the fabrication of SMPs.

TABLE 2 Actuators in soft robotics.

Actuator type	Description	Application
Magnetic actuators	Utilise polymers with magnetic fillers (e.g. NdFeB particles, iron oxide particles) that respond to external magnetic fields, inducing deformation through magnetic forces or torques.	Biomimetic 3D structures like grippers, flowers, butterflies
SMPs	SMPs can remember and return to a programed shape upon external stimulus. Includes one-way SMPs (irreversible shape change) and two-way SMPs (reversible shape change).	Soft crawling robots, hydraulic actuators, shape-changing structures
Pneumatic actuators	Utilise elastomer structures with embedded chambers that expand upon pressurisation, leading to bending and other complex motions.	Bioinspired soft robots capable of extension, contraction, bending, twisting
Electroactive actuators	Utilise materials that expand or contract in response to electrical stimuli. Includes IPMCs that operate at low voltages and DEAs that require higher voltages.	Biomedical devices, soft robotics (e.g. active catheters, grippers, microfluidic valves)
Acoustic actuators	Utilise acoustic waves to induce movement, often using piezoelectric materials. This approach allows the creation of small devices without the need for electric or pneumatic lines.	Acoustic-responsive actuators, bioinspired systems with potential future applications in soft robotics

Abbreviations: DEA, dielectric elastomer actuator; IPMC, ionic polymer metal composite; SMP, shape memory polymer.

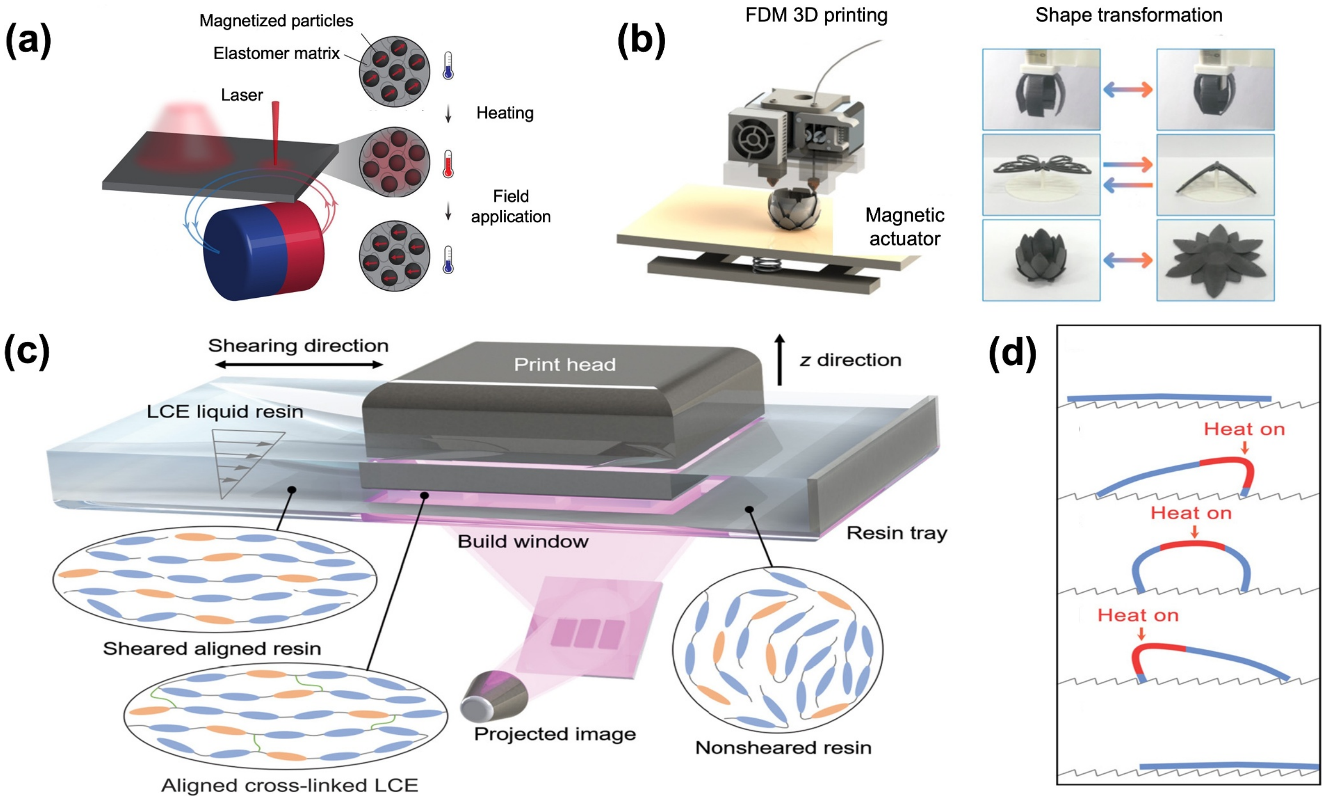

FIGURE 3 Fabrication of soft actuators with the use of different 3D printing techniques. (a) Schematics of DLP for magnetic soft robots in UV-curable elastomeric composites (reproduced from ref. [54]). (b) FDM printing process and printed biomimetic structures for magnetic soft actuators (reproduced from ref. [28]). (c) Schematics of DLP for LCE-based soft actuators (reproduced from ref. [65]). (d) DLP-printed earthworm-inspired soft crawler that crawls on a ratchet surface (reproduced from ref. [65]). FDM, fused deposition modelling; LCE, liquid crystal elastomer.

In contrast to one-way SMPs, two-way SMPs manifest a reversible shape transformation process between initial and temporary shapes throughout the operational cycle [62, 66, 67]. A liquid crystal elastomer (LCE) is a typical two-way SMP. When the heating temperature is higher than the phase transition temperature or the cooling temperature is lower than the phase transition temperature, the aligned mesogens within the LCE undergo reversible transitions between the nematic and isotropic phases, accompanied by macroscopic shape morphing [62, 67]. DI and DLP are common fabrication methods, as shown in Figures 3c and 3d [65]. By exploiting shear forces during printing, DLP aligns liquid crystal mesocrystals, as shown in Figure 3c. The functionality of the printed LCE is exemplified by a soft crawling robot mimicking an earthworm (Figure 3d). SMPs have also been combined with hydraulic applications. Qing et al. developed a 3D/4D-printed hydraulic actuator using a stiff SMP section along with a high-resolution soft elastomer part, enabling the presence of microfluidic channels of various shapes to enable different required movements for fluid transportation [68].

3.3 | Pneumatic actuators

Pneumatic soft actuators have attracted considerable attention because of their advantages of safety, cost-effectiveness, and ease of fabrication [29, 69]. Pneumatic actuation is consistently the most widely adopted actuating device in 3D/4D printing for soft robotics, demonstrating its popularity and significance in the field. This is due to their generally simpler manufacturing and the large variety of 3D-printing methods that can be used to develop them, as demonstrated by Wang et al. [70] and discussed by Stano et al. [71]. Other factors that encourage the implementation of pneumatic actuators are their lightweight-ness as well as low cost in fabrication, as stated by Xavier et al. in a review where the use of these pneumatic actuators is discussed in depth [72]. Pneumatic actuators typically adopt elastomer structures with embedded chambers. As illustrated in Figure 4a–10b, the pneumatic system provides the air pressure via designated channels [29]. Upon pressurisation, the channels expand primarily in regions with greater compliance or lower stiffness due to their lower resistance to stretching. Consequently, the structure encasing the expanding volume undergoes bending to accommodate the asymmetric elongation of the two opposing walls of the channel. With an actuated network of channels, soft pneumatic actuators exhibit versatile motion abilities, including extension, contraction, bending, or twisting [50, 75–78]. Various 3D-printing methods, including polyjet 3D-printing, DLP, FDM, DIW, and SLA, have been used to fabricate bioinspired pneumatic soft robots [30, 50, 76, 79]. The

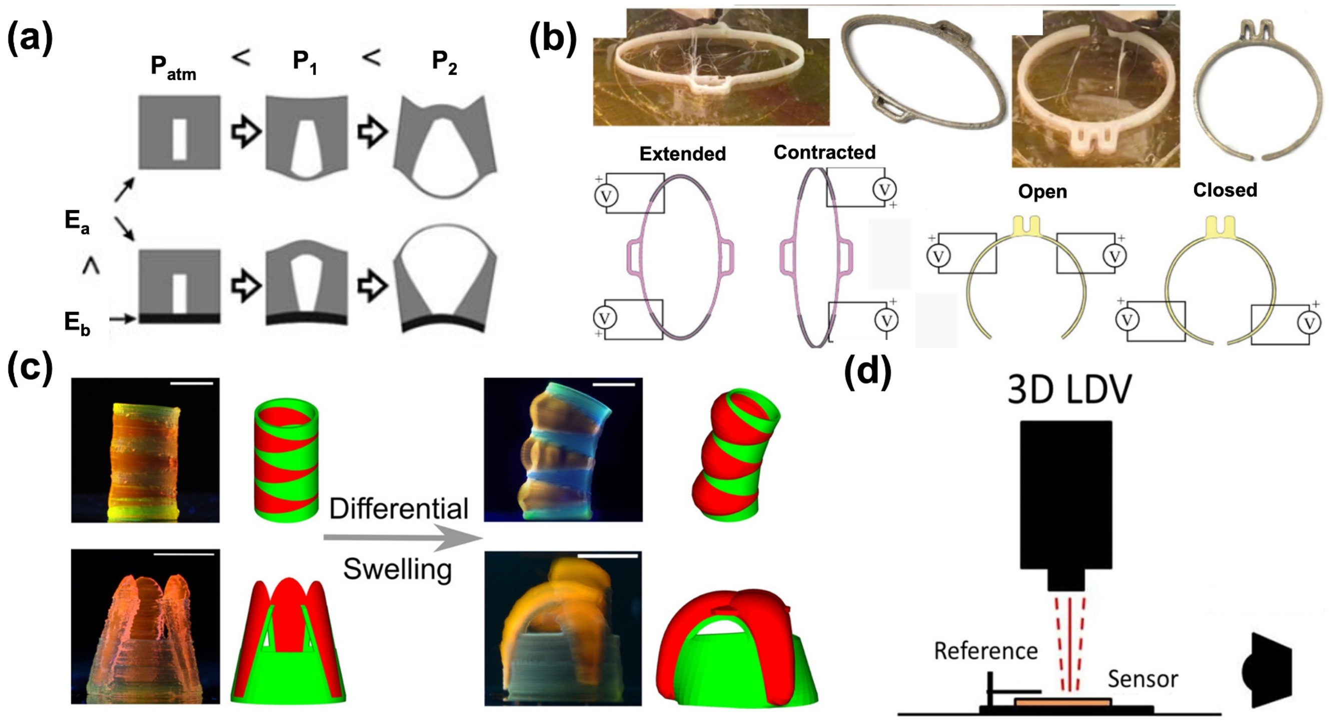

FIGURE 4 Examples of printed pneumatic and electroactive soft actuators. (a) Working mechanism of a pneumatic bending actuator. P_{atm} represents the minimum pressure required for deformation. P_1 and P_2 represent the pressures under different pressurisation conditions. E_a and E_b represent the Young's Modulus of different materials (reproduced from ref [29]). (b) Working mechanism of a 3D-printed IPMC soft crawling robot inspired by a caterpillar (reproduced from ref. [73]). (c) Demonstration of bilaterally and radially symmetric tubes with periodically spaced segments (reproduced from ref. [31]). (d) Use of a vibrometre for acoustic actuator measurements of a piezoelectric polymer (reproduced from ref. [74]). IPMC, Ionic polymer metal composite.

modifiability and flexibility offered by direct 3D printing have increased its use in the fabrication of pneumatic bioinspired soft actuators (Figure 4b) [73].

The use of pneumatic actuators has extended in many directions because of their versatility. Lalegani Dezaki et al. implemented a multi-material 3D-printing technique using FDM to combine the properties of a conductive TPU and varioShore TPU [80]. The conductive properties of the former endow the soft pneumatic actuator with sensory responsiveness, enabling it to act as a gripper, a commonly bioinspired device. Similarly, pneumatic actuators have been used to develop biodegradable soft robots and to advance machine learning to further enhance their usage in other technologies [81, 82]. The variety and extent of work seen in pneumatic actuators for use in soft robots makes it one of the primary methods used to develop biomimetic and bioinspired devices.

3.4 | Electroactive actuators

Electroactive actuators, which utilise materials that expand or contract in response to external stimuli like electricity, are inspired by the motions of biological organisms that often relies on organised movements of anisotropic tissues. [83]. This biological characteristic has been explored to induce complex motions in synthetic soft materials [84]. A common technique used to produce these actuators involves the use of a responsive material in a section of the actuator to produce different interactions, such as heat. Liu et al. strategically 3D printed segments composed of swelling and non-swelling materials to achieve diverse functionalities. Benefiting from multi-material DIW 3D-printing techniques, dual-gel tubes composed of an active thermally responsive swelling gel (poly(N-isopropylacrylamide) and a passive thermally non-responsive gel (polyacrylamide) were fabricated (Figure 4c) [31].

As mentioned before, IPMCs act as electroactive polymers, where an ion-exchange membrane is placed between two electrode layers [50, 83, 85–87]. Unlike dielectric elastomer actuators (DEAs), which necessitate high activation voltages (e.g. kilovolts) [30, 73, 79], IPMCs can operate with significantly lower voltages (e.g. a few volts). Besides, IPMCs possess desirable attributes such as flexibility and functionality within aqueous environments [88], even at sub-micron scales [89]. These characteristics render IPMCs appealing for utilisation in biomedical devices and soft robotics. Examples include active catheters [90], manipulators [30], grippers [91], and microfluidic valves and pumps [92].

Dielectric actuators operate with an electric charge, causing movements that these systems require, such as deformation or compression, as mentioned before. Ceramic dielectric actuators are commonly used, but some polymers, such as PVDF, have been proposed to form soft actuators [93]. Silicone-based materials or polymers are usually used in the fabrication of these electric actuators, although hydrogels are also used. For example, in work by Carpi et al., actuators were fabricated 'in stacks in series mechanically and parallel electrically' [94], and their second configuration utilised a helical structure, with both allowing for the construction of different shapes observed in nature.

3.5 | Acoustic actuators

While a more complex method, acoustic actuation can facilitate the creation of smaller devices due to the lack of need for electric or pneumatic lines, as these can be manipulated through acoustic waves. Examples can be found in hydrogels where acoustic vibrations can enable movement in the system. Some systems have been able to utilise soft materials to develop acoustic actuators. Zöller et al. used a piezoelectric microphone embedded into a soft actuator made of silicone and used acoustics to 'reflect, refract and attenuate' the signal that using a helically wound polyester thread to control movement [95]. In addition to bioinspired features, Domingo-Roca et al. fabricated an acoustic responsive actuator fabricated through SLA, using piezoelectric polymers with the incorporation of barium titanate ($BaTiO_3$) particles that enable this response, as shown in Figure 4d [74], where a vibrometre is used to measure the acoustic response of the material. While there is much room for improvement in acoustic simulation, reported simulation studies demonstrate its potential for bioinspired actuation and could constitute the long-term future of the field.

4 | APPLICATIONS OF BIOMIMETIC/ BIOINSPIRED ACTUATORS

3D-printing processes affect manufacturing by enabling the production of intricate micro/mesostructures, enhancing design flexibility, allowing for mass customisation, minimising waste, and facilitating rapid prototyping. These advancements offer numerous benefits across various industries (e.g. medical, waste removal, and environmental monitoring) and within biomimicry and biomimetic [96, 97]. By replicating natural patterns and geometries, engineers and designers can develop products with enhanced performance, durability, and sustainability [96].

4.1 | Muscles and organ actuators

One of the major applications of soft actuators is to replicate the movement of muscle tissue and organs, notably skeletal muscles, heart, and lungs. Pneumatic and piezoelectric actuators are more common due to the offered movement and their more extensive understanding.

4.1.1 | Skeletal muscle actuators

One of the basic principles of muscle actuation is to follow the natural motion of expansion and contraction, as shown by de Pascali et al., where biomimetic artificial muscles are built with the mentioned purpose [98]. Pneumatic actuators called GeometRy-based actuators that contract and elongate (GRACE) can perform contraction and elongation. This is achieved via a simple mathematical model and an additive manufacturing technique in a one-step process. This can be applied to different 3D-printing techniques, as they can produce these actuators using different soft materials (such as resins and TPUs) and techniques (such as SLA and FDM). The GRACE model consists of 'a closed series of elliptical arcs whose concavity alternates to generate the pleats'. This can be clearly observed in Figure 5a. These studies provide actuators with contraction and expansion similar to those of skeletal muscles.

As demonstrated by Peele et al., many musculature designs of actuators with a high degree of freedom have been 3D printed [99]. The printed soft actuator's cross section and the flexible movements of each chamber are displayed as it is pressurised. The employment of techniques that use high resolution can be beneficial for the development of complex muscle-like actuators, and the benefit of elastomers being susceptible to high resolution 3D-printing can be exploited for flexible movements.

Muscles require electrical responses to perform their activities, so the use of dielectric actuators has also been explored to replicate them. Cao et al. fabricated a bioinspired soft actuator via DEAs because of its ability to perform skeletal-like movements with self-sensing capabilities [100]. Here, the cerebellum was used as inspiration because of the ability of motor learning to make a motion controller able to control the non-linear behaviour of the DEA. These in tandem provide more control to the system, as shown in simulations and applications. A simple fabrication method uses two annular PET layers of different thicknesses to attach pre-stretched films, with carbon grease smeared on both sides to add an anode and a cathode.

Similarly, inspired by the fibrous architectures found in muscular hydrostats (Figure 5b), multi-degree-of-freedom (multi-DOF) soft actuators were fabricated via a DIW-based multi-material 3D-printing platform [30]. The bioinspired fibre architecture could be fabricated seamlessly, eliminating the need for a separate casting and assembly process. These devices presented a high actuation speed (5.54 Hz), 123,000 cycles of lifetime, a payload to weight ratio of 26, and significant output forces (~16 N). The soft robot demonstrated versatile motions, including elongation, contraction, or twisting, which were achieved by programming material properties and printed architectures [30].

While the range of muscle movements can be limited to expansion and contraction, different muscles require various

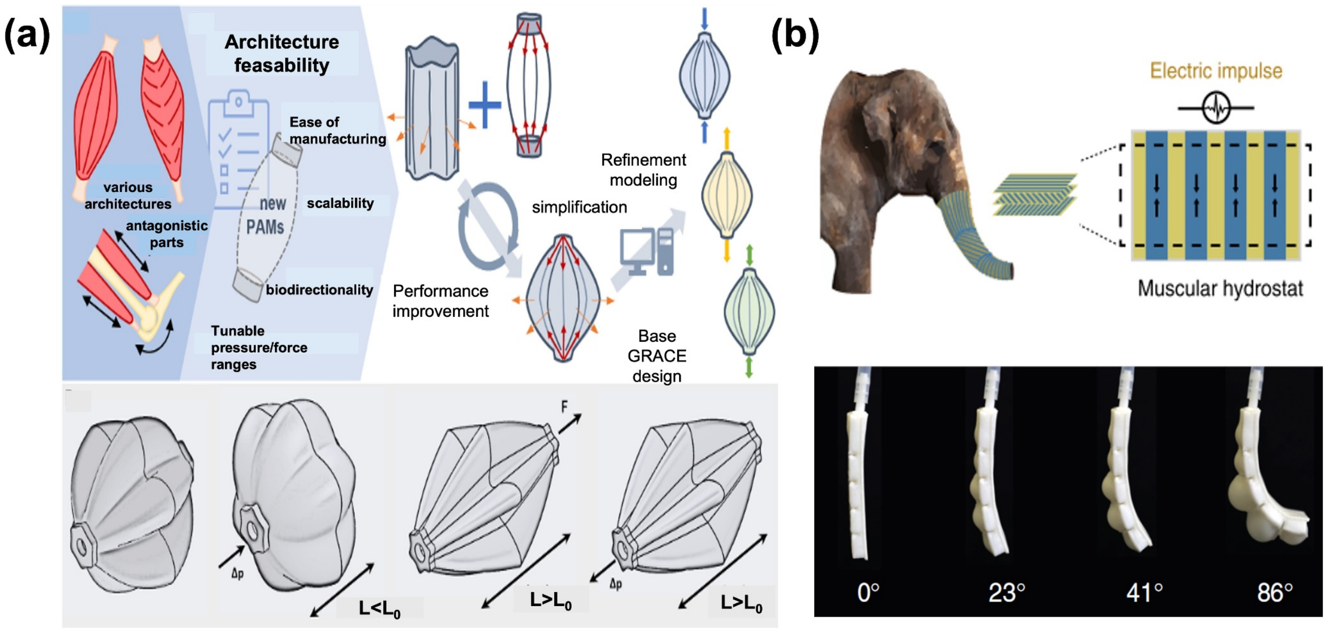

FIGURE 5 Soft actuators influenced by muscle movements through bioinspiration and biomimicry. (a) Schematic depicting of GeometRy-based actuators that contract and elongate, displaying their contraction and elongation (reproduced from ref. [98]). (b) Schematic illustration of the muscular hydrostat and 3D-printed bioinspired soft actuators (reproduced from ref. [30]).

elements of actuation, which explains the spectrum of techniques practiced for their development.

4.1.2 | Heart actuators

Soft actuators have been implemented not only to replicate the beating function of the heart and explore ventricle pumping but also to explore all chambers of this vital muscular organ.

Pneumatic actuators can be used to replicate some of the compression movements seen in the heart as it pumps. Owing to the large strain and work being done in this area, most are focused on movement in the left ventricle (LV), as this chamber pumps all the blood into the body. Some soft actuators have been built to replicate this motion using silicone-based actuators. Vignali et al. prepared a LV model using vacuum actuation, where a pneumatic setup was developed to analyse the 'radial and longitudinal displacement, twist rotation, and ejection fraction' [101]. The pneumatic pump is able to perform mock circulatory loops, as it reproduces LV movement.

Other soft actuators with pneumatic features have been developed with the use of hydrogels because of their already discussed biocompatibility. Cheng et al. used DIW to develop biomimetic soft robots that can have tentacle-like motion [32]. Using these features, compression can be created in pneumatic chambers of a 3D-printed heart model, as shown in Figure 6a. The expansion and compression of the model is significant, and it can transport different biomaterials, as the hydrogels possess engineered vessels, replicating the transportation features of nutrients observed in humans.

Some actuation systems use shape memory alloys and ionic polymer metal alloys embedded in a dielectric soft elastomer to control motion. Walters et al. developed this dielectric actuator. This device, instead of replicating a heart's mechanical properties, strictly focuses on the pumping function, with the intent of generating an artificial muscle for EcoBots [103]. The design of this model mimics heart functionality with hollow structures and a soft region that can be compressed to manipulate airflow, manufacturing soft regions with shape memory alloys. The dielectric actuators are made from silicone rubber and act as artificial muscles.

Microbial fuel cells can perform actuating functions through the generation of electricity, creating deformation in heart, like lungs. Another electrically based method is the use of piezo-bending actuators, as shown by Mannhardt et al. [104]. Here, the actuators perform both isometric and auxotonic contractions, and by placing the devices in hollow silicone tubes, up to 24 muscles can be contracted in both directions and analysed in parallel. This system is connected to a circuit board that can use the collected data of contraction kinetics for engineered heart tissue.

While most models of the heart for actuation use the LV, pneumatic actuation causes negative pressure inside the chamber. The fabrication of a pulsatile actuator can mitigate this effect. Bezerra et al. developed this method by using rigid and flexible reservoirs, with the ability to replicate both the internal volume of the end-systolic volume and the cardiac output, respectively [105]. The rigid reservoir was made with ABS and flexible through the printing of a rubber like material.

Recently, the pulsation of the right ventricle (RV) has also been studied. Singh et al. developed a biohybrid model combining an endocardial scaffold with a robotic right ventricle [102]. As illustrated in Figure 6b, the latter uses simple McKibben actuators to perform its pulsating feature,

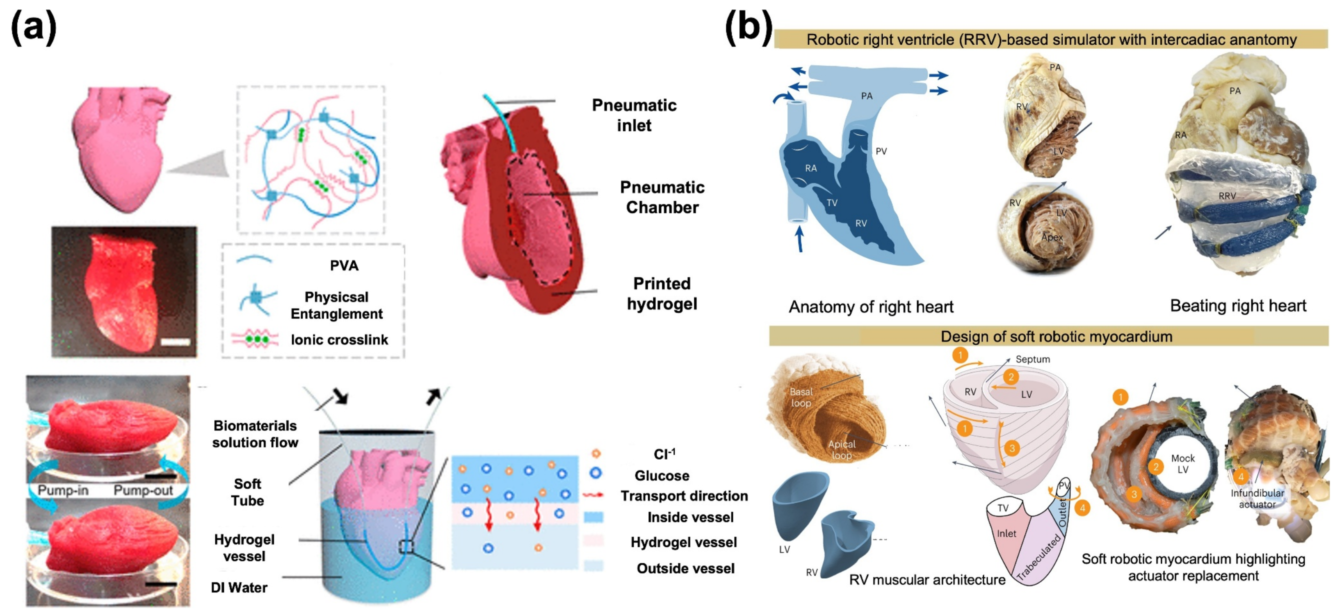

FIGURE 6 Fabrication of actuators and models inspired by the compression/contraction movement of the heart. (a) Functionality of soft pneumatic actuators in a heart model, displaying pumping and transfer of nutrients (reproduced from ref. [32]). (b) Design of a robotic right ventricle with the incorporation of McKibben actuators to provide pulsating features (reproduced from ref. [102]). LV, left ventricle; PA, pulmonary artery; PVA, polyvinyl alcohol; RA, right atrium; RV, right ventricle; RRV, robotic right ventricle; and TV, tricuspid valve.

which can be used for surgical practice, such as tricuspid valve repair. The actuators produce an input pressure of 172 kPa while generating a 25% axial contraction and a 117% radial expansion. The complexity of the heart as an organ can make the fabrication of an accurate model more difficult than that of the lungs, but there have been advances in the development of these devices.

4.1.3 | Lung actuators

As lungs possess extremely specific contraction and expansion patterns, the use of soft actuators to manufacture surrogates or models for medical applications has been explored. Interestingly, many studies on lung-replicating actuators have integrated 3D-printed moulds to perform these actuations. An example of this is work by Ranukel et al., where the use of platinum-coated silicone actuators from 3D-printed moulds that act as alveoli can result in deformation similar to that observed in the lungs [106]. A strong correlation was observed in their deformation, as shown in Figure 7a. They claim that while the system presents various similarities to lungs in terms of deformation, there are many limitations in meeting the different mechanical properties found in lungs, which is a theme found for any artificial surrogates, especially those formed from 3D-printed moulds, as mentioned previously, as well as sample to sample variance.

While the use of pneumatic actuators is predominantly used for lung-like behaviour, performing the contraction and deformation movement required can be reproduced by replicating structures seen in the organ itself. Shin et al. proposed the development of deformable lung phantoms with 3D-printed airways, as shown in Figure 7b [107]. Rubber and foams were used as soft, flexible actuators to replicate the deformation processes of the lung. First, the polyurethane foam was 3D printed to form airways and then placed into a mould with a liquid-expanding foam to obtain a full lung. Then, these were infused in iodine to replicate the density of the human lung. Breath-hold CT scans were used to quantify the reproducibility of the lung density and its motion, deformation and position. The breath-hold CT scans revealed minimal changes in the lung measurements over 8 weeks, demonstrating high reproducibility. This finding is significant because it helps overcome a key challenge in the development of reliable lung imaging devices.

Similarly, devices such as soft actuators for flexible bronchoscopes have been developed for lung studies. These devices are used to observe lung airways internally, so they must be flexible and soft to avoid harm to patients. Surakusumah et al. designed a flexible bronchoscope that uses a soft tip, with flexibility offered by an actuator [108]. This mixture was cast into a 3D-printed mould using silicone rubber. Adding knitted fibres in two different orientations (braiding angles) allows the soft actuator to twist and bend, creating a half-sphere movement.

4.2 | Animal and plant actuators

3D printing intersects with biomimicry in the creation of complex structures that mimic natural forms and functions. Nature has evolved incredibly efficient and optimised structures. This can be seen in creatures such as worms, plants, and fish, which serve as inspiration for designs regarding 3D printing.

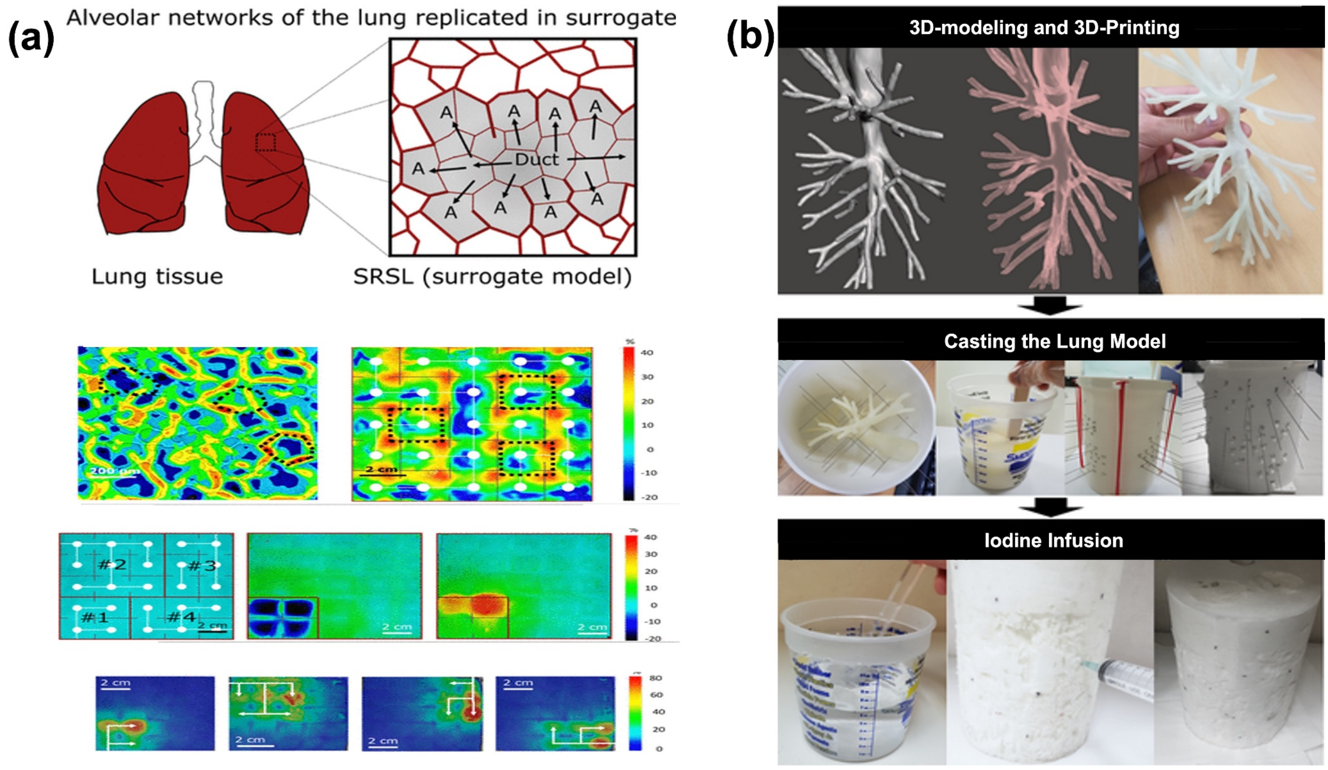

FIGURE 7 Different aspects of lung deformation and movements seen in soft actuators. (a) Deformation and structural comparisons between lung tissue and silicone-based actuators (reproduced from ref. [106]). (b) Fabrication process of a phantom lung model using 3D-printed mould casts (reproduced from ref. [107]).

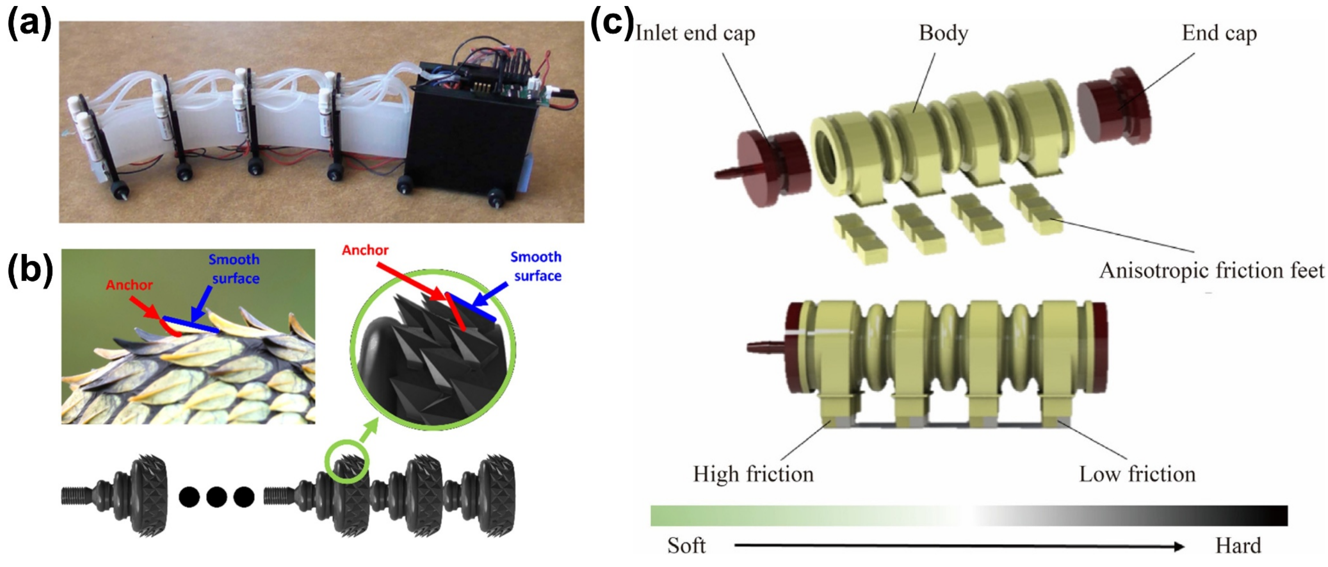

FIGURE 8 Biomimetic and bioinspired soft actuators for crawling animals. (a) Undulating a biomimetic snake actuator (reproduced from ref. [33]). (b) Schematic illustration of the modularised snakeskin soft robot (reproduced from ref. [79]). (c) Biological structure and schematic of the caterpillar-inspired crawling actuator (reproduced from ref. [76]).

4.2.1 | Snake actuators

Owing to their effective movements in various environments, snakes have inspired many biomimetic designs. In 2013, a bioinspired pneumatic soft robotic snake (Figure 8a) capable of undulating in a manner like its biological counterpart without human intervention was made by Onal and Rus [33]. The tail and body were created using 3D-printed moulds cast with soft silicone. The autonomous soft snake robot features on-board actuation, power, computation, and control capabilities, achieved through four bidirectional fluidic elastomer actuators arranged in series on passive wheels to create a travelling curvature wave from head to tail along its body.

Lee et al. drew inspiration from snakeskins to develop a DLP-printed pneumatic actuator (Figure 8b) [79]. The anisotropic friction force generated by the snake-inspired scales facilitated forward propulsion of the robot body. The snake-scale structure allows the robot to easily customise its movement characteristics by changing the number and orientation of modular units. This adaptable soft robot was able to deliver weights up to 2.5 times its mass across various environments, such as flat surfaces, tubes, inclines, and underwater scenarios [79].

4.2.2 | Worm actuators

Similar to snakes, the flexibility of worms, due to their lack of exoskeletons, has been a subject of interest in the replication of these movements in soft actuators. In 2019, Calderón et al. investigated earthworm locomotion mechanisms, focusing on deformable structural units called metameres that generate peristaltic body motions essential for burrowing and crawling [109]. Inspired by these mechanisms, researchers have proposed a novel pneumatically driven soft robot capable of mimicking a single metamere's motions and functionalities. The cast silicone robot was made from 3D-printed moulds. A sensing scheme (based on an earthworm's skin) was added, utilising stretchable liquid circuits to measure strain and detect pressure variations. This robot shows potential for applications in constrained environments such as movement through pipes.

Drawing inspiration from caterpillars or worm-like organisms, a 3D/4D-printed IPMC soft crawling robot comprising linear actuator (body) and gripper (leg) components (Figure 8c) was fabricated [76]. By selectively applying the voltage to specific locations, contraction and extension were realised by the body actuator, whereas opening and closing actions were realised by the leg actuator. The soft crawling robot demonstrated its motion capability within curved plastic tubes through a passive synergistic locomotion pattern involving coordinated movements between the robot's body and feet.

4.2.3 | Plant actuators

Plants exhibit unique contractions and movements, from the extension of stems to the compression and expansion of flowers. This variety of movements has made them a subject of study for biomimicry and biomimetic actuation. In some of these cases, 3D-printed moulds are used as a baseline to develop these models. Cooper et al. designed a soft-robotic spiral gripper inspired by the secure grip of twining plants on small targets in tight spaces (Figure 9a) [34]. This design

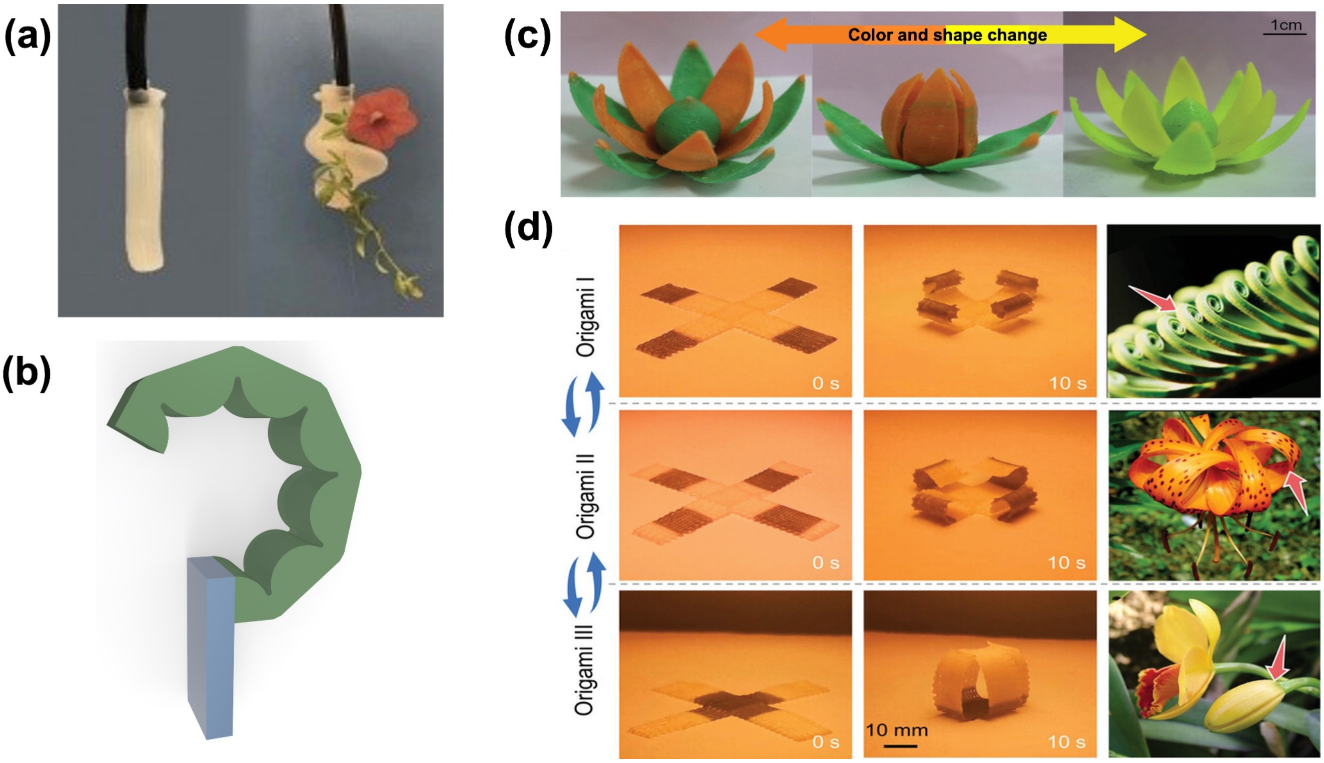

FIGURE 9 Soft actuators based on movements observed in different plants and flowers. (a) Spiral gripping mechanism inspired by twinning plants (reproduced from ref. [34]). (b) Schematic illustration of soft vacuum actuators inspired by the sporangium of fern trees. (c) SMP-based FDM-printed soft actuator that mimics flower blooms and colour changes (reproduced from ref. [110]). (d) LCE-based reprogrammable soft actuators with four branches to mimic different flower bloom patterns (reproduced from ref. [110]).

performs twining motions and firmly grasps objects in confined spaces, facilitating precise gripping. The gripper incorporates a high-birefringence fibre optic twisting sensor for measuring the twining angle and external disturbance data and was constructed via the use of a silicone cast in 3D-printed moulds. Its single-channel pneumatic control enables parallel and gentle gripping of elongated objects in tight spaces, which is crucial for executing twining and twisting motions in soft robots.

Tawk et al. proposed another modular robot to mimic the sporangium of fern trees via FDM 3D-printing technology (Figure 9b) [30]. The modularity concept enables the soft pneumatic actuator to achieve multi-DOFs and adjustable body lengths by manipulating the number of 3D-printed hinges. The resulting robots demonstrated a high actuation frequency (5.54 Hz), payload-to-weight ratio of up to 26 times, and output forces of 16 N [30].

Figure 9c illustrates a soft actuator resembling a flower. The flower was 3D-printed with PLA infused with a thermochromic pigment [110]. Upon heating by a hotplate, the actuator underwent shape morphing that mimics flower blooming, whereas the thermochromic pigment exhibited colour changes such as natural floral dynamics. 3D/4D-printing of functional materials, like flowers (Figure 9c-d), offers avenues for electric, magnetic, or optical actuation of SMP-based bioinspired and biomimetic soft actuators [111–114].

4.2.4 | Frogs

Frogs can grip and attach to surfaces easily while emitting significant amounts of moisture; their toepads and tongues' dynamics are mostly studied. The dynamic friction performance of frog toepad inspired surface patterns was investigated in 2020 by Banik and Tan [115]. The frog toepad morphology was replicated and fabricated through 3D-printing with TPU. Among the bioinspired models tested, the double-layered studded hexagonal pattern exhibits the best wet traction performance and most closely resembled a real frog's toepad. This bioinspired frog toepad design can offer enhanced wet friction for products requiring improved surface wet traction, such as underwater and surgical grippers.

A frog inspired dielectric actuator, by Shao et al., consists of trilayer polymer-based dielectric elastomers that were fabricated to replicate the motion of the rolling and extending of a frog's tongue [116]. Here, a multilayered structure uses polymers as both structural and active materials, and electrical charges induce morphing and snapping, which can be tied to tongue extension and contraction.

4.2.5 | Fish and cephalopod actuators

The features provided by movement in fish and cephalopods are of great interest because of their unique motions and intricacies in liquid flow.

SunBot, created by Wang et al. in 2023, is a robotic system designed to study and replicate fish-inspired tearing manipulations, specifically those seen in sunburst butterflyfish [117]. The system utilised a biomimetic tail made of cast soft silicone and rigid plastic 3D-printed components. The robotic platform carried out floating manipulation tasks while displaying swimming locomotion capabilities, allowing manipulation functions. SunBot successfully shows the potential for using existing open-water swimmers for new manipulation functions.

In 2023, a research study by Xiong et al. presented a novel bio-robot inspired by flying fish, an aerial-aquatic animal known for its gliding capabilities over water surfaces [118]. The robotic design incorporated collapsible wings integrated with soft hydraulic actuators, with the implementation of pliable actuators in the aquatic-aerial robot. The soft actuators were fabricated from cast silicone, which created a flexible and hydrophobic membrane. These actuators in collapsible wings allowed robot control in aerial and aquatic environments due to being designed for a 90-degree bending motion while also granting the ability to respond to external forces.

SoFi, a soft robotic fish (Figure 10a) designed for minimally invasive underwater exploration, was introduced in 2018 by Katzschmann et al. [119]. The SoFi exhibited agile swimming manoeuvres and continuous recording capabilities. Its soft robotic actuator design allows for lifelike undulating tail

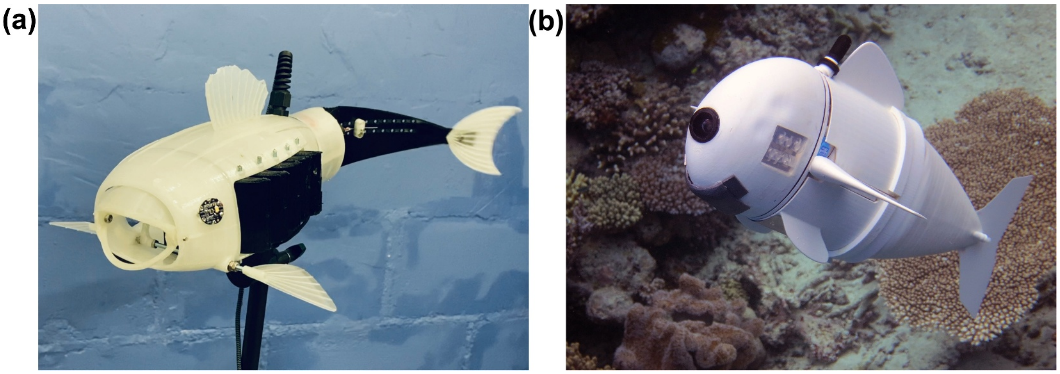

FIGURE 10 Biomimetic and bioinspired robots with actuating movements based on fish. (a) Soft robotic fish developed for underwater exploration (reproduced from ref. [119]). (b) Gilbert, a biomimetic fish-like robot used for pollution removal, was inspired by fish gills (reproduced from ref. [35]).

motion, overcoming the limitations of traditional thruster-based and tethered underwater vehicles. This design generated minimal turbulence and did not scare marine life, making SoFi a valuable tool for observing and studying aquatic life and ocean dynamics.

Gilbert is a biomimetic pollution-filtering robot inspired by fish gills and built in 2023 (Figure 10b) by Sidall et al. [35]. To investigate the filtration mechanism of gills, Gilbert used 3D-printed ABS gill plates with a soft interstitial nylon mesh to trap microplastic particles from aquatic environments. The robot combines hard materials for actuation with a soft flexible filtration mechanism. Additionally, its fish-like undulating tail propulsion allows smooth movement through water. Gilbert demonstrated the potential of biomimicry and 3D-printing in addressing environmental issues such as targeted waste cleanup.

The use of 3D-printed moulds is also prevalent in these models, as a 2020 study by Xie et al. explored soft actuators modelled after octopus' arms, focusing on the advantages of conical-shaped actuators over traditional cylindrical forms [120]. The suckers and the arm were cast with silicone from 3D-printed moulds. The results revealed that, compared with cylindrical actuators, tapered actuators with suckers possess increased gripping power and require larger forces to be detached from surfaces. This research study offers insights for developing next-generation soft actuators for gripping objects and highlights the functional significance of arm taper angle variability in octopus species.

4.2.6 | Turtles/tortoises

Flippers in turtles and tortoises create oscillatory movements that can be replicated in soft actuation. For turtles, these movements are generally used as they swim, and the adaptation of these movements is observed in the work of Hubbard et al., where the oscillatory flow of the flippers is used to create a soft robot with integrated fluid circuity [121]. This robot is manufactured using Polyjet 3D-printing. The 3D/4D-printed soft robot inspired by a turtle enables the 'flippers' to generate a constant flow of fluid input, as they find themselves connected to soft actuators. Interestingly, the assembly of this robot is generated through one step of 3D-printing, including the incorporation of modular components within the robot itself. In the case of tortoises, their crawling actions inspire a pneumatic actuating device produced by Wu et al., where the challenge of terrain adaptation of crawling actuators is addressed through the fabrication of bionic legs that can bend in three different dimensions [122]. The shape of a tortoise's legs serves as an inspiration for these pneumatic actuators. The developed robot is capable of linear motion (0.97 body lengths per second, or BL/s) and turning (25.4° per second), as well as carrying up to 28 times its weight. Owing to their dominant terrain, turtles and tortoises provide unique movements that can be recreated in soft robotics.

5 | FUTURE OUTLOOK

These advancements in bioinspired and biomimetic soft robots and actuators hold promise for revolutionising technology and enabling innovative solutions for exploration and environmental studies without disturbing natural habitats. While these results are encouraging, ongoing research is vital to address material limitations and realise their full potential across practical applications.

In the pursuit of 3D/4D-printed soft flexible biomimetic robots and components, existing limitations must be addressed. The scarcity of highly flexible filaments has constrained the use of traditional FDM in soft robotics, limiting its applications to moulds and components. While DIW can 3D print highly flexible materials such as silicone, its restricted resolution hinders complex part fabrication. SLA and DLP offer improved resolution but lack materials as flexible as silicone. SLA, DLP and Polyjet are limited in overall size of the structure.

Furthermore, although biomimicry is gaining traction, it remains an underutilised approach in manufacturing [79]. To progress towards our goal, future endeavours should explore non-filament fed FDM, enhance DIW resolution and complexity, develop more flexible SLA materials, resource efficient materials, and encourage broader adoption of the biomimicry mindset within the research community.

As ongoing research and development continue, we expect significant progress in combining soft robotics and 3D printing to unlock the full potential of biomimicry, revolutionising technology and promoting sustainable progress in the years to come. The development of systems that employ biomimicry will continue to grow in different areas, as one of the main focuses of scientific research is the replication of movements and actions observed in nature. While there are still some complications associated with fully applying these methods in current technologies, as seen in this review, extensive work is being done to employ some of these fascinating behaviours in technological advances. The development of soft robots and actuators corresponds to only a section of work in biomimicry, as a large variety of these actions can provide functionalities of all kinds.

Another topic discussed in this review is the application of some of these bioinspired and biomimetic devices in the development of artificial organs, both devices and models. While there has been development in the replication of some of the movements in muscles and organs, such as the heart and lungs, there are still developments to be made, as the complexities of these movements have somewhat limited their operation. However, these models can potentially be used for certain applications, such as surgical practice, as well as for further understanding some of their behaviours mechanically, as it is more convenient to create these scaffolds rather than obtaining an in vivo specimen. In conjunction with the development of biomimicry and bioinspired models, soft robots and actuators for surgical practice can aid in understanding and mimicking human organs, which can increase the success rate of some complex surgeries. It is imperative that work on biomimicry and biomimetic devices continues to develop to achieve significant medical advances in terms of surgical efficiency and comprehension of the structure and behaviour of some of these organs.

Finally, 3D printing waste minimisation aligns with biomimetic concepts of resource efficiency and circularity, contributing to sustainable manufacturing practices and reducing environmental impact, unlike subtractive methods, which generate significant waste. However, due to the iterative nature of 3D printing and biomimicry, the reduced material waste during manufacturing may be negated. To claim a more sustainable manufacturing method, researchers need to continue working with AI and machine learning. Machine learning and AI can help researchers find ideal 3D printer settings and practices, which can reduce the overall number of iterations for designs. This sustainability aspect is increasingly valued in today's manufacturing landscape, pointing towards efforts to reduce resource consumption and promote eco-friendly practices in the future.

Overall, a large variety of factors influence the development of soft actuators and robots for biomimetic and bioinspired applications. All these elements influence growth in this area, and efforts in different fields and points of interest can increase the evolution of biomimicry and bioinspired research. A significant variety of methods and materials have been used to do so, and this variety is expected to grow exponentially in the foreseeable future.

ACKNOWLEDGEMENTS

S.S.S. and A.G.O. contributed equally to this work. K.Q. acknowledges the support from the Startup Funds and the Cougar Cage Funds at Washington State University and National Science Foundation (Research Traineeship program Award No. DGE 2244082 and Graduate Fellowship Grant Award No. 2235552 for S.S.S.). S.Y. acknowledges the support from the Startup Funds at Stony Brook University and the National Science Foundation (Award No. ECCS-2238363).

CONFLICT OF INTEREST STATEMENT

The authors declare no competing financial interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Sparks, S.S., et al.: 3D-printed biomimetic and bioinspired soft actuators. IET Cyber-Syst. Robot. e70001 (2024). https://doi.org/10.1049/csy2.70001