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# Soft Actuators and Robots Enabled by Additive Manufacturing

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## Keywords

soft robots, additive manufacturing, 4D printing, integrated soft actuators and sensors

## Abstract

Soft robotic systems are human friendly and can mimic the complex motions of animals, which introduces promising potential in various applications, ranging from novel actuation and wearable electronics to bioinspired robots operating in unstructured environments. Due to the use of soft materials, the traditional fabrication and manufacturing methods for rigid materials are unavailable for soft robots. 3D printing is a promising fabrication method for the multifunctional and multimaterial demands of soft robots, as it enables the personalization and customization of the materials and structures. This review provides perspectives on the manufacturing methods for various types of soft robotic systems and discusses the challenges and prospects of future research, including in-depth discussion of pneumatic, electrically activated, magnetically driven, and 4D-printed soft actuators and integrated soft actuators and sensors. Finally, the challenges of realizing multimaterial, multiscale, and multifunctional 3D-printed soft robots are discussed.

## 1. INTRODUCTION

In the past several decades, the development of traditional robots with rigid actuation and transmission mechanisms has tremendously promoted economic growth, especially in the fields of automated assembly and manufacturing in structured environments. Because these conventional rigid robots are made from hard materials, they offer limited capabilities to perform complex motions with compliance and adaptability, which restricts the applications for interaction with humans or unstructured environments (1). Soft robotic systems, which have emerged more recently, are made of soft materials that can generally sustain large deformation while inducing little pressure or damage when maneuvering through confined spaces. Owing to the inherent compliance of the soft materials, soft robotic systems are human friendly and can mimic the complex motion of animals, which introduces promising potential in various applications, ranging from novel actuation and wearable electronics to bioinspired robots and biohybrid robots operating in unstructured environments (2).

Materials used in traditional robotic systems have moduli on the order of $10^9$–$10^{12}$ Pa. By contrast, soft robotic systems are often composed of materials with moduli on the order of $10^4$–$10^9$ Pa, similar to those of natural organisms (3). Due to the use of these soft materials, the traditional fabrication and manufacturing methods for rigid materials, such as machining, joining, and shearing and forming, are unavailable for soft robots, creating challenges for the fabrication and manufacturing of soft robots (4).

In the beginning, because the functions and structures of soft robots were simple, methods such as molding, reinforcement, thin-film manufacturing, shape-deposition manufacturing, and bonding were sufficient to fabricate soft robotic systems. As the functions of soft robots have increased, however, researchers have needed to design and manufacture soft material structures with multiple materials and different sizes. Recently, 3D printing has emerged as a novel manufacturing method that offers more freedom to design complex geometries compared with other manufacturing methods (5).

3D printing is an additive manufacturing process, defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" (6, p. 389; see also 7). It can produce parts with sophisticated and complex geometries with no need for postprocessing, built from custom-made materials and composites with near-zero material waste, while being applicable to a diversity of materials, including smart materials such as shape-memory polymers and other stimulus-responsive materials. Therefore, it offers increasing design freedom and allows designers and engineers to create unique products that can be manufactured at low volumes in a cost-effective way. Common 3D-printing techniques include fused deposition modeling (FDM), direct ink writing (DIW), selective laser sintering (SLS), inkjet, and digital light processing (DLP).

The advantages of 3D printing make it a promising fabrication method for the multifunctional and multimaterial demands of soft robots. For soft robots, it enables the personalization and customization of the materials and structures. In the past few decades, there has been a significant trend toward using 3D-printing technology to fabricate soft robots for various applications. There have been several comprehensive review articles on 3D printing and soft robotics; the existing reviews on soft robotics have focused mainly on the issues of materials, mechanics, and physics, such as soft robots based on origami structure (8), untethered soft robots (9), stiffness-tunable soft robots (10), magnetically driven soft robots (11, 12), and closed-loop control of soft robots (13). The additive manufacturing of soft robots has also been reviewed; for example, reviews by Wallin et al. (3) and Gul et al. (14) focused on 3D-printing methods and the associated soft robots fabricated by 3D-printing methods, reviews by Momeni et al. (15) and Khoo et al. (16) surveyed the

3D-printed active materials and their applications in soft robotics, and reviews by Truby & Lewis (5) and Bourell (17) presented 3D-printing methods for fabricating soft materials. However, there is still a lack of reviews of effective additive manufacturing methods for manufacturing specific soft robots. With the rapid development of soft robots, this topic may draw more attention from researchers in the fields of robotics and automation.

In this review, we provide perspectives on the manufacturing methods for various types of soft robotic systems and discuss the challenges and prospects of future research. We provide in-depth discussion of pneumatic, electrically activated, magnetically driven, and 4D-printed soft actuators and integrated soft actuators and sensors. **Figure 1** shows a timeline of milestones in the development of 3D printing of soft robots, starting with a pneumatically driven, multigait soft robot manufactured using a printed mold in 2011, and then extending to soft robots driven by electrical, magnetic, temperature, and chemical fields and soft robots 3D printed using FDM, inkjet, DLP, stereolithography (SLA), DIW, and multimaterial 3D-printing methods. **Figure 2** plots the cumulative distributions of the 3D printing of soft robots based on the year and the printing methods. It can be observed that the development of 3D printing of soft robots is still in the early stage.

This article is organized as follows. Section 2 summarizes the various types of 3D-printing methods. The existing 3D-printing fabrication methods for soft robots are summarized in Section 3. Section 4 discusses multiscale 3D-printing and novel printing methods for soft robots. Discussion and conclusions are given in Section 5.

## 2. 3D-PRINTING METHODS

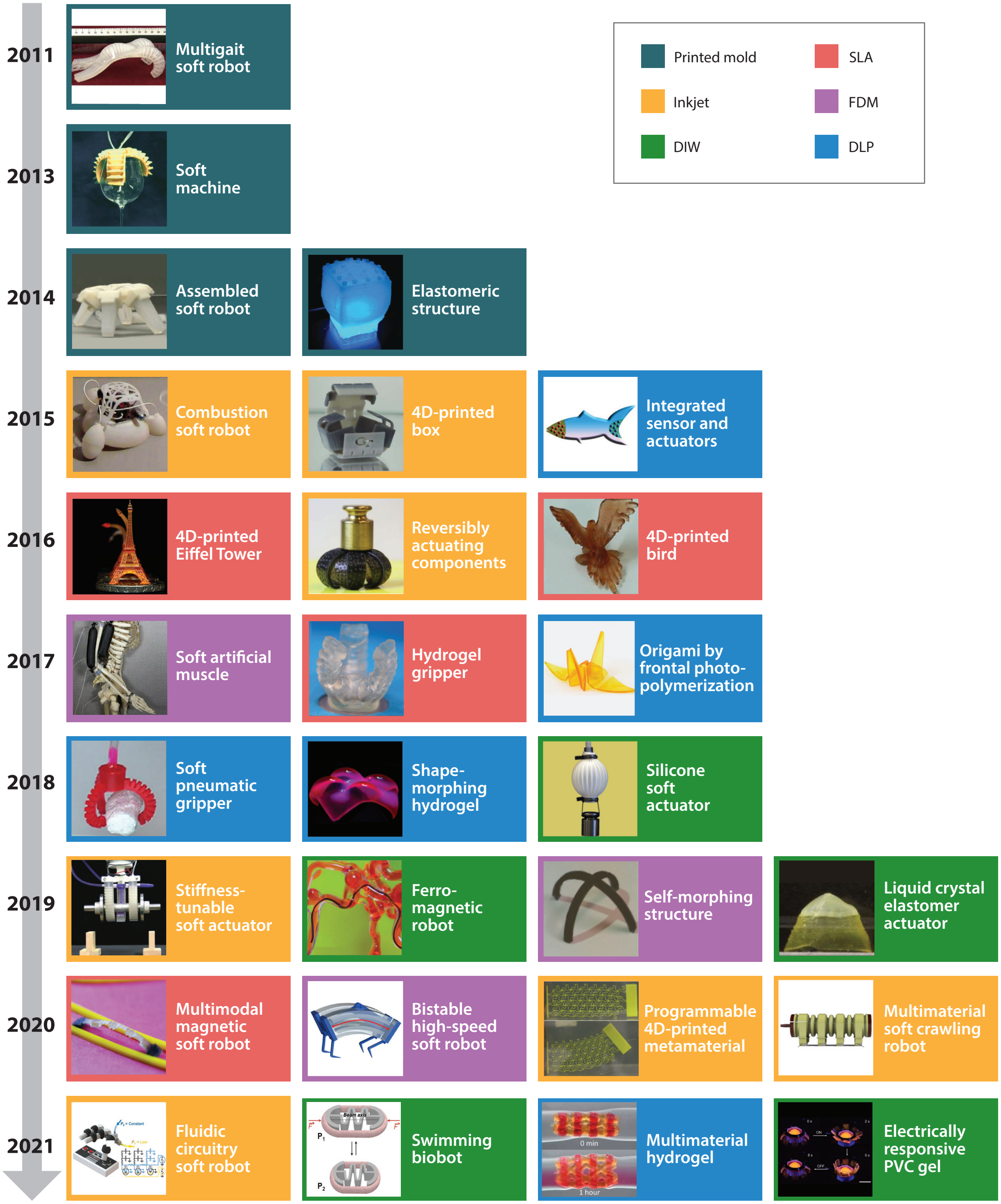
This section describes various 3D-printing methods used to manufacture soft robots, including FDM, DIW, SLS, inkjet and DLP. These methods are illustrated in **Figure 3**, and their precision, advantages, and disadvantages are summarized in **Table 1**.

In FDM, a solid thermoplastic filament is extruded through a heated nozzle to melt or soften the filament, then deposited on a build tray to fabricate 3D structures layer by layer. FDM is the most common 3D-printing technology because of its simplicity and low cost. However, compared with other 3D-printing technologies, it has a longer operation time and lower resolution. Moreover, only a few thermoplastic polymers, such as acrylonitrile butadiene styrene and polylactic acid, are commercially available for FDM 3D printing.

DIW is another widely used 3D-printing method to fabricate pneumatic soft actuators. A DIW printer uses a print head similar to that of an FDM printer. Instead of a solid thermoplastic material, a DIW printer deposits a viscoelastic ink or paste. During printing, the nozzle moves across the build platform and extrudes the viscoelastic ink under pressure to fabricate the desired 3D object layer by layer.

In SLS, a bed of solid thermoplastic powder is selectively heated by a scanning laser. The irradiation causes localized melting and fusion of the material. The powder is then cast to recoat the bed, and the process is repeated. SLS can be used to fabricate complex structures without external support and is suitable for mass production.

Inkjet is a noncontact printing technology that deposits tiny droplets of low-viscosity ink on a build tray using thermal or piezoelectric technology. Inkjet printers often combine ink nozzles and a UV light source in one platform. The photocurable liquid resin is polymerized immediately after being sprayed on the build tray by illumination with a UV light source. Jetting and solidification are iteratively repeated until the entire object is built. The commonly used materials in inkjet are commercial materials: a soft, rubbery material (Tango or Agilus), with a modulus of ~10 MPa, and a rigid material (Vero), with a modulus of ~1 GPa at room temperature. Inkjet can be used to print



*(Caption appears on following page)*

**Figure 1** (*Figure appears on preceding page*)

Development of soft actuators and robots manufactured by printed mold, SLA, SLS, FDM, inkjet, DLP, DIW and MM3D methods. (*2011*) Multigait soft robot, adapted with permission from Reference 18. (*2013*) Soft machine, adapted with permission from Reference 20. (*2014*) Assembled soft robot, adapted with permission from Reference 19; elastomeric structure, adapted with permission from Reference 21. (*2015*) Combustion soft robot, adapted with permission from Reference 165; 4D-printed box, adapted from Reference 135 (CC BY 4.0); integrated sensor and actuators, adapted with permission from Reference 175. (*2016*) 4D-printed Eiffel Tower, adapted from Reference 133 (CC BY 4.0); reversibly actuating components, adapted from Reference 127 (CC BY 4.0); 4D-printed bird, adapted with permission from Reference 130. (*2017*) Soft artificial muscle, adapted from Reference 55 (CC BY 4.0); hydrogel gripper, adapted with permission from Reference 42; origami by frontal photopolymerization, adapted from Reference 140 (CC BY 4.0). (*2018*) Soft pneumatic gripper, adapted with permission from Reference 44; shape-morphing hydrogel, adapted with permission from Reference 124; silicone soft actuator, adapted from Reference 29 (CC BY 4.0). (*2019*) Stiffness-tunable soft actuator, adapted with permission from Reference 40; ferromagnetic robot, adapted with permission from Reference 91; self-morphing structure, adapted from Reference 117 (CC BY 4.0); liquid crystal elastomer actuator, adapted with permission from Reference 146. (*2020*) Multimodal magnetic soft robot, adapted with permission from Reference 101; bistable high-speed soft robot, adapted from Reference 24 (CC BY 4.0); programmable 4D-printed metamaterial, adapted with permission from Reference 198; multimaterial soft crawling robots, adapted with permission from Reference 39. (*2021*) Fluidic circuitry soft robots, adapted from Reference 48 (CC BY 4.0); swimming biobot, adapted with permission from Reference 203; multimaterial hydrogel, adapted from Reference 50 (CC BY 4.0); electrically responsive PVC gel, adapted with permission from Reference 204. Abbreviations: DIW, direct ink writing; DLP, digital light processing; FDM, fused deposition modeling; MM3D, multimaterial 3D printing; PVC, polyvinyl chloride; SLA, stereolithography; SLS, selective laser sintering.

complex structures with high resolution, but the failure strains of the two materials are relatively low—generally less than 200% for the soft, rubbery material and less than 20% for Vero.

In DLP, a bath of liquid photopolymer is selectively exposed to light. The liquid resin polymerizes into a solid layer in response to photoirradiation. The object is then translated, and liquid

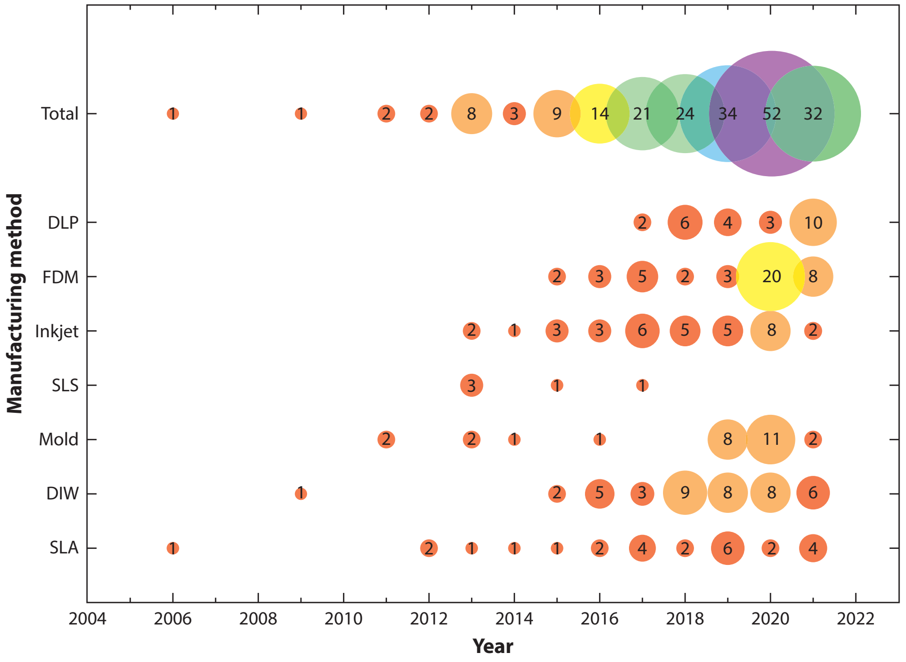


**Figure 2**

Cumulative distributions of 3D-printed soft actuators and robots based on year and printing methods. The data are provided in **Supplemental Table 1**. Abbreviations: DIW, direct ink writing; DLP, digital light processing; FDM, fused deposition modeling; SLA, stereolithography; SLS, selective laser sintering.

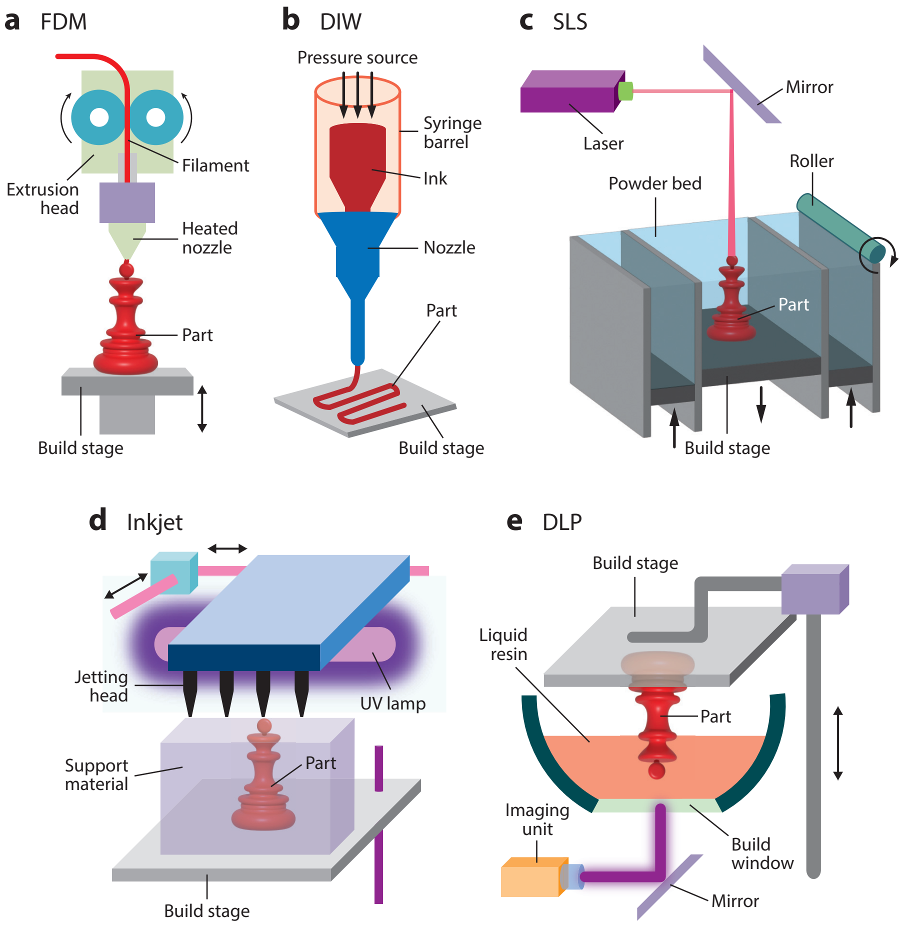


**Figure 3**

Common additive manufacturing methods. (*a*) In FDM, a solid thermoplastic filament is extruded through a heated nozzle to melt or soften the filament, then deposited on a build tray to fabricate 3D structures layer by layer. (*b*) A DIW printer deposits a viscoelastic ink or paste to fabricate the desired 3D object layer by layer. (*c*) In SLS, a bed of solid, thermoplastic powder is selectively heated by a scanning laser. (*d*) Inkjet is a noncontact printing technology that deposits tiny droplets of low-viscosity ink on a build tray using thermal or piezoelectric technology. (*e*) In DLP, the liquid resin polymerizes into a solid layer in response to photoirradiation. Abbreviations: DIW, direct ink writing; DLP, digital light processing; FDM, fused deposition modeling; SLS, selective laser sintering.

recoats the interface. The next layer is similarly exposed. Like inkjet, DLP can provide high printing resolutions, but it allows the use of customized materials. SLA is a technique similar to DLP that uses a UV laser instead of a digital light projector, leading to a slower build speed.

## 3. 3D PRINTING OF SOFT ACTUATORS AND ROBOTS

This section presents different additive manufacturing methods for soft actuators. We review 3D-printing methods for various soft actuators, including pneumatic, electrically activated, magnetically driven, and 4D-printed soft actuators. We also review 3D-printed soft actuators with integrated soft sensors.

**Table 1 Precision, advantages, and disadvantages of 3D-printing methods**

| Printing method | Precision | Advantages | Disadvantages |
|---|---|---|---|
| FDM | 100 μm (22) | Lower initial investment cost<br>High surface finish<br>Ease of making complex shapes | Slow process<br>Poor accuracy and precision |
| DIW | 1–100 μm (5) | Ability to use various materials | Slow process<br>Poor resolution and surface finish |
| SLS | 100 μm (3) | Does not require any external support<br>Suitable for mass production | High cost of manufacturing<br>Requires postprocessing |
| Inkjet | 50 μm (205) | Ease of multimaterial printing<br>Fast process<br>Good accuracy | High cost of manufacturing |
| DLP | 1–50 μm (206–208) | Fast process<br>High resolution | High cost of manufacturing<br>Enables less materials to be used |

Abbreviations: DIW, direct ink writing; DLP, digital light processing; FDM, fused deposition modeling; SLS, selective laser sintering.

## 3.1. Pneumatic Soft Actuators

Pneumatic soft actuators, consisting of an elastomer structure with embedded chambers, are popular because they are lightweight, safe, low cost, and easy to fabricate (18, 19). The soft actuators can extend, contract, bend, or twist in response to pressurized fluid depending on the structural design. Many 3D-printing methods have been used to fabricate pneumatic soft actuators (20, 21) with different material properties, actuation forces, and magnitudes of strains, including FDM, DIW, inkjet, and DLP.

Pneumatic soft actuators fabricated by FDM show relatively small deformation because materials generally exhibit small failure strains. For example, a soft gripper has been 3D printed using thermoplastic elastomer with FDM technology (22) (**Figure 4*a***). The soft gripper can grasp and lift heavy objects with a high payload-to-weight ratio that results from the thermoplastic elastomer's relatively large modulus, whereas the soft gripper's deformation is relatively smaller as it is easy to break. Using sequenced soft bending mechanisms, Xie et al. (23) 3D printed a robot that can climb pipes with various diameters, inclinations, and curvatures. Tang et al. (24) developed spine-inspired high-speed and high-force soft robots by leveraging tunable snap-through bistability, which demonstrates the abilities of high-speed locomotion (2.68 body lengths per second) and high-speed underwater swimming (0.78 body lengths per second). Pneumatic soft actuators for locomotion or assisted elbow flexion have also been printed using the FDM method (25, 26).

Pneumatic soft robots that were made with the DIW method and based on silicone elastomer generally show a larger deformation (27–33). For example, Schaffner et al. (29) developed pneumatic silicone actuators exhibiting programmable bioinspired architectures and motions (**Figure 4*b***). These actuators consist of an elastomeric body and reinforcing stripes with a well-defined lead angle. Elongation, contraction, or twisting motions can be achieved by varying the lead angle. Plott & Shih (28) demonstrated a sphere-like balloon exhibiting a diametric expansion of up to 200% and a pneumatic finger actuator that can fully articulate more than 30,000 circles before failure due to the silicone elastomer's excellent performance. However, complex structures are difficult to achieve using the DIW method.

Inkjet can fabricate pneumatic soft actuators with high resolution and complex structures (34, 35). Pneumatic soft robots made with the inkjet method are easier to break than those made with silicone elastomers. Drotman et al. (36) used the inkjet method to 3D print soft robots with bellowed soft legs capable of navigating unstructured terrain. Zhang et al. (37) used the inkjet method

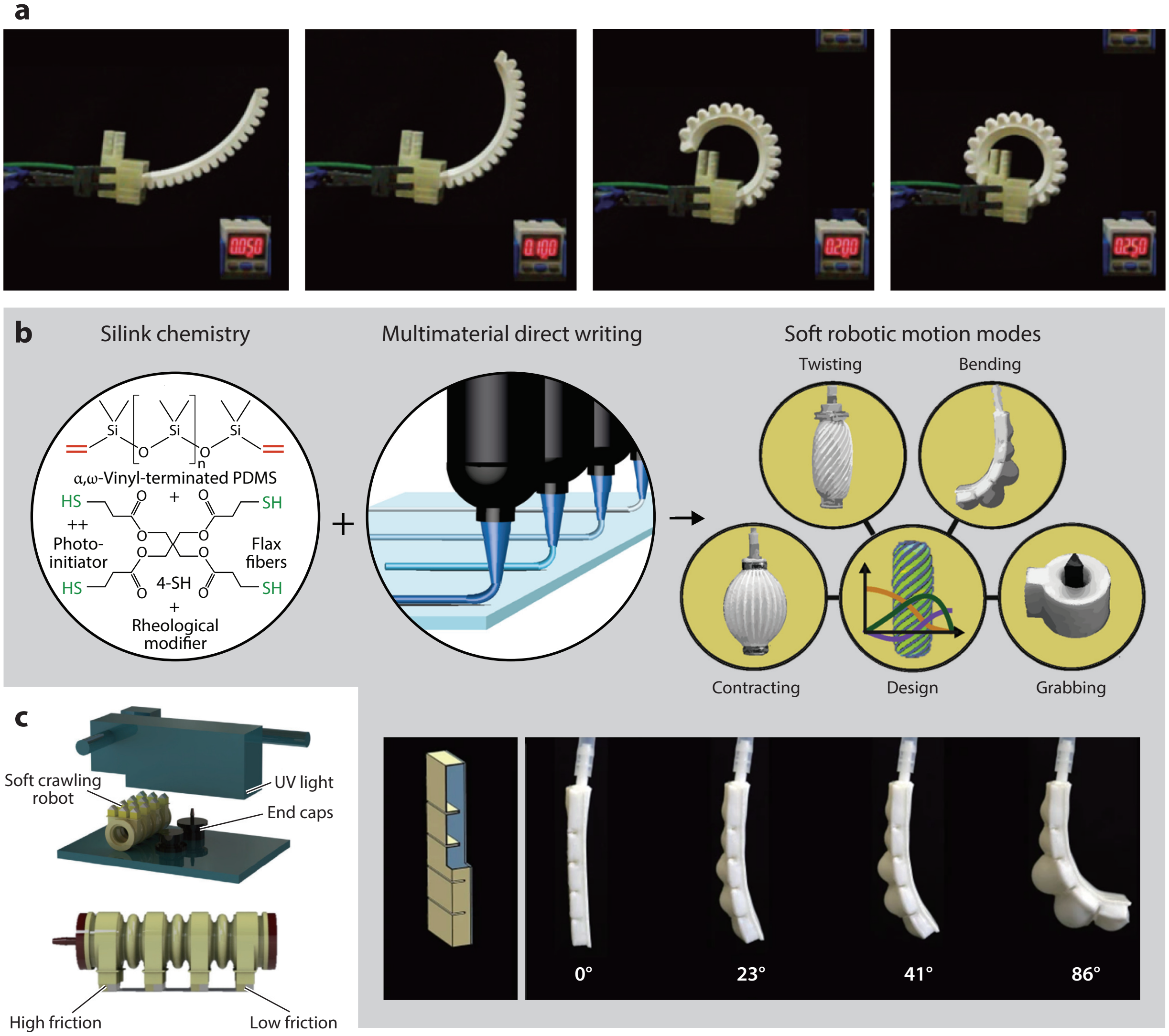


**Figure 4**

3D-printed pneumatic soft actuators. (*a*) A soft gripper made using the FDM method. Panel adapted with permission from Reference 22. (*b*) Pneumatic silicone actuators exhibiting programmable bioinspired architectures and motions, printed by DIW. Panel adapted from Reference 29 (CC BY 4.0). (*c*) A caterpillar-inspired soft crawling robot that is directly 3D printed with multiple materials and without a complex assembly process. Panel adapted with permission from Reference 39. Abbreviations: DIW, direct ink writing; FDM, fused deposition modeling; PDMS, polydimethylsiloxane.

to 3D print pneumatic modularized rigid–flexible integrated soft finger actuators that can be directly assembled into an anthropomorphic hand. MacCurdy et al. (38) used the inkjet method with multimaterial 3D printing to create a functional hexapod robot. Taking advantage of the multimaterial printing capability, Sheng et al. (39) 3D printed a caterpillar-inspired soft crawling robot with multiple materials and without a complex assembly process (**Figure 4*c***). Zhang et al. (40) developed a stiffness-tunable soft actuator 3D printed using inkjet and DIW methods (**Figure 5*a***). The body was printed using the inkjet method, and the conductive Joule-heating circuit inside

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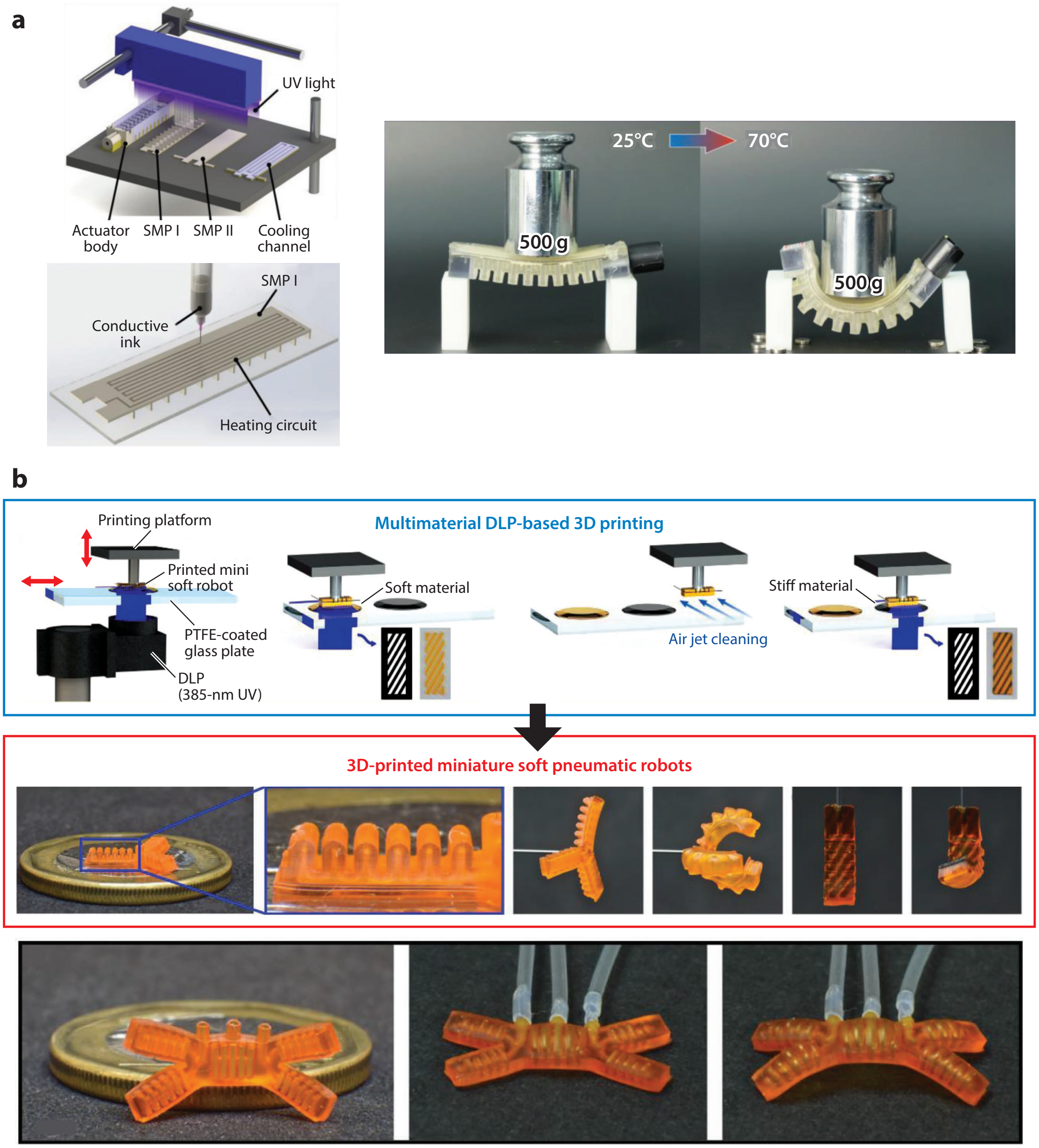

**Figure 5**

3D-printed pneumatic soft actuators. (*a*) A stiffness-tunable pneumatic soft actuator made with a combination of the inkjet and DIW methods. Panel adapted with permission from Reference 40. (*b*) A miniature pneumatic soft actuator made with a high-resolution multimaterial DLP method. Panel adapted with permission from Reference 45. Abbreviations: DIW, direct ink writing; DLP, digital light processing; PTFE, polytetrafluoroethylene; SMP, shape-memory polymer.

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was written using the DIW method to induce stiffness changes under an electric–thermal stimulus. The stiffness-tunable gripper can grasp and lift objects with arbitrary shapes and various weights spanning from less than 10 g to 1.5 kg.

DLP is another 3D-printing method that can fabricate pneumatic soft actuators with photopolymerization. For example, soft pneumatic actuators can be 3D printed using UV-curable elastomers (41, 42), commercial photopolymers (43), or TangoPlus (44). Adding ethylene acrylic acid into the TangoPlus resin decreases the Young's modulus of the printed material and increases the failure strain, which has been used to 3D print pneumatic soft actuators (45) (**Figure 5*b***). Silicone networks can be printed that participate in orthogonal cross-linking mechanism–photocurable thiol-ene reactions and condensation reactions, which show simultaneously large ultimate strain ($\sim$400%), low elastic modulus ($<$700 kPa), and high toughness and strength (46). Combining DLP and DIW methods enables soft pneumatic actuators to be 3D printed to achieve programmable deformation (47). Soft robots comprising fully integrated fluidic circuitry have also been fabricated via PolyJet 3D printing (48).

Overall, many 3D-printing methods have been used to fabricate pneumatic soft actuators, depending on the necessary material properties, actuation forces, and strain magnitudes. DIW has been widely used to manufacture pneumatic soft actuators based on soft silicone elastomers, showing a large stretchability. Printing processes based on the melting of solids, such as FDM, are usually used to print thermoplastic polyurethane material. The fabricated pneumatic soft actuators show relatively less deformation because polyurethanes are stiff and their failure strains are low, and they are therefore unlikely to meet high deformation demands. Inkjet and DLP methods have been used to manufacture high-resolution soft actuators with complex structures. However, there is a need to develop UV-curable materials that are highly deformable and fatigue resistant to remove the obstacles to fabricating high-resolution pneumatic soft actuators for engineering applications (49, 50).

## 3.2. Electrically Activated Soft Actuators

Electrical actuation is a common soft actuation method. Electrically driven soft actuators are usually composed of electroactive polymers, such as ionic polymer–metal composites (IPMCs) and dielectric elastomer actuators (DEAs).

IPMCs generally consist of a solvent swollen ionic polymer membrane (typically Nafion, plated with a noble metal) laminated between two thin electrodes (such as gold–carbon nanotubes) (51, 52). When an electric potential is applied to the electrodes, the negatively charged side attracts cations, causing it to swell. The swelling of one side generates a bending motion in the IPMC. Due to their advantages of large bending deformation and low driven voltage, IPMCs have shown promising applications in underwater soft robots.

IPMCs have usually been fabricated using sputtering deposition, solution casting, or electroplating, all of which are unsuitable for forming complex 3D structures (53). 3D-printing techniques have been introduced to fabricate complex IPMCs. For example, Carrico et al. (54) used the FDM method to create electroactive polymer structures for applications in soft robots and bioinspired systems. The process begins with extruding a precursor material into desired structures, followed by a chemical functionalized process and an electroless plating process. To fabricate electrically driven soft actuators with high strain (up to 900%), high stress (up to 1.3 MPa), and low density (0.84 g $\mathrm{cm}^{-3}$), Miriyev et al. (55) used FDM to 3D print a composite consisting of polydimethylsiloxane-based silicone elastomer as a matrix material and ethanol as the active fluid (**Figure 6*a***). The artificial muscle can be electrically actuated using a thin resistive wire and low-power characteristics (8 V, 1 A), exhibiting significant expansion–contraction ability. Carrico et al.

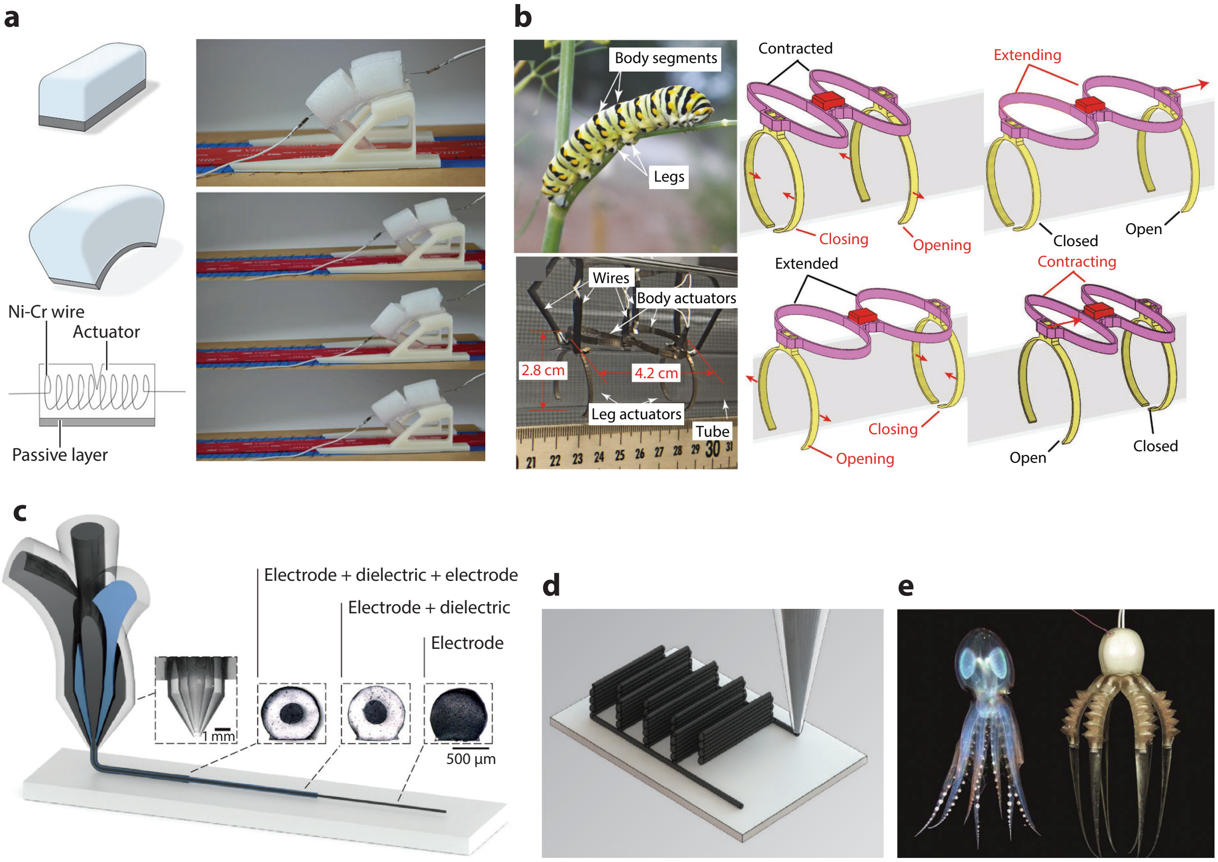


**Figure 6**

3D-printed electrically driven soft actuators. (*a*) A sleigh robot and its locomotion, powered at 8 V and 1 A. The robot consists of a PDMS-based silicone elastomer as a matrix material and ethanol as the active fluid. Panel adapted from Reference 55 (CC BY 4.0). (*b*) A caterpillar-inspired IPMC soft crawling robot fabricated with FDM. The robot contains two legs and two body sections with electrical connections. Panel adapted from Reference 56 (CC BY 4.0). (*c*) Multimaterial DEAs 3D printed using multicore-shell 3D printing. Panel adapted with permission from Reference 74. (*d*) 3D printing of a compliant electrode using DIW. Panel adapted with permission from Reference 68. (*e*) A fully 3D-printed soft jellyfish mimetic robot that actuates through voltage application to rheological fluid in its joints and cavities. Panel adapted with permission from Reference 84. Abbreviations: DEA, dielectric elastomer actuator; DIW, direct ink writing; FDM, fused deposition modeling; IPMC, ionic polymer–metal composite; PDMS, polydimethylsiloxane.

(56) also used FDM to fabricate another IPMC-based soft crawling robot inspired by a caterpillar (**Figure 6*b***).

Unlike IPMCs, DEAs are usually composed of a dielectric elastomer membrane coated on both sides with compliant electrodes. When a high voltage is applied, the Maxwell stress between the electrodes squeezes the dielectric elastomer membrane, leading to an expansion in area and a decrease in thickness (57). Based on this working principle, different DEA configurations (such as rolling, conical, and folded) have been proposed to transfer the planar deformation into multiple actuation modes, including elongation, bending, and rotation (58). Due to their large strain, fast response, and high energy density, DEAs have shown huge potential in soft robotics (59–61).

DEAs are made mainly of commercial dielectric membranes (such as VHB 4910/4905 or Silpuran film 2030) and electrodes (such as carbon grease and carbon nanotubes). Commercial materials have the advantage of accessibility and low cost, but the limitations on size are also apparent. To this end, some fabrication processes have been proposed, including blade casting (62), spin coating (63), and pad printing (62, 64). These processes are usually accompanied by issues related to efficiency, geometry flexibility, and scalability. The development of 3D printing creates compelling opportunities for DEAs to achieve fast and effective fabrication. However, there are some special requirements to develop 3D printing of DEAs: (*a*) to decrease the applied voltage, the printed dielectric elastomer membrane needs to be thin (<100 μm); (*b*) to increase the fault tolerance of DEAs, the printed dielectric elastomer membrane must be uniform, smooth, and reliable; and (*c*) fabricating DEAs requires multimaterial 3D-printing technologies.

Recently, several early attempts to 3D print DEAs have been reported. The first work on 3D printing DEAs was from 2009 and used an inkjet printing method to fabricate a dielectric elastomer membrane (acrylic-based photopolymer materials) with a thickness of 90 μm (65). McCoul et al. (66) used a piezoelectric inkjet system to 3D print a silicone-based dielectric elastomer membrane with a thickness of 2 μm, generating a 6.1% area strain. The FDM method has also been utilized to print thermoplastic polyurethane–based dielectric elastomer membranes that can cause 4.73% strain in all directions, and the effects of the printing path have been analyzed, demonstrating preferential deformation direction (67). To fabricate DEAs with in-plane contractile actuation, Chortos et al. (68) used a DIW printing method to print interdigital electrodes and then created 3D DEAs by encapsulating these electrodes with polyurethane acrylate, generating a 9% actuation strain (**Figure 6*d***). In addition, the supporting frames of DEAs can be printed using an FDM method, enabling them to achieve large deformation and multiple functions (69). Multimaterial 3D-printing methods such as SLA (70), the aerosol-jet-printing method (71), DIW (72, 73), and multicore-shell 3D printing (74) have also been adopted to fabricate DEAs (**Figure 6*c***). DEAs with a membrane-based structure can be manufactured using 2D-based pad-printing methods (75).

Electrical fields can also be coupled with magnetic or thermal fields to actuate soft actuators (76). Shape-memory alloys are widely used in electrical–thermal soft actuators. Various 3D-printing methods have been used to fabricate different matrices (77–81). For example, Gul et al. (81) used DIW with epoxy and polyurethane to develop a spider-mimicking three-legged soft robot, which was able to achieve a maximum forward speed of 2.7 mm $s^{-1}$ with an input voltage of 3 V and 250 mA on a smooth surface. A soft robot inspired by highly deformable animal caterpillars was 3D printed using inkjet; shape-memory-alloy coils were embedded into the robot to act as structural elements and actuators under the stimulus of electricity, which can generate complex, robust gaits on different inclines (82, 83). Zatopa et al. (84) used the inkjet method to fabricate a soft, octopus-like robot driven by an electrorheological fluid valve that can stop the fluid flow, build pressure in the robot, and actuate six soft, tentacle-like bending actuators (**Figure 6*e***). Phamduy et al. (85) also used the inkjet method to develop an electromagnetically driven untethered robotic fish propelled by customized solenoid actuators.

### 3.3. Magnetically Driven Soft Actuators

Pneumatic, hydraulic, tendon-driven, and shape-memory-alloy-based actuators often become complicated with sophisticated direction control; with external power sources and additional tethers for actuation, robots actuated by these methods have limited regions of applicability in sophisticated environments. Magnetic actuation can circumvent these issues.

Magnetic materials can be roughly classified into two categories: soft magnetic and hard magnetic. Soft-magnetic materials, such as iron-, nickel-, and silicon-based alloys, are characterized by high magnetic susceptibility and saturation magnetization but relatively low remanence and coercivity. These materials are strongly attracted to a magnet. By contrast, hard-magnetic materials are generally obtained by embedding hard-magnetic particles (e.g., neodymium–iron–boron alloy) into a soft polymeric matrix (e.g., silicone rubber or gels). Hard-magnetic materials exhibit a large coercivity, enabling the realization of complex shape transformations under magnetic actuations (86). Untethered, reversible, rapid, and programmable actuations—which are essential for performing soft robotic functions such as grasping, walking, swimming, jumping, and transporting—can be induced by manipulating the internal magnetization profiles and external magnetic field.

However, knowledge gaps exist in developing multimodal soft robots with small sizes in terms of functionality, fabrication, and actuation efficiency. In recent years, multimaterial 3D-printing techniques have provided a practical solution to address several challenges associated with the simple and precise manufacturing of magnetically driven soft actuators. Magnetically responsive soft actuators have been fabricated mainly using the DIW and DLP methods. In both methods, the magnetically responsive particles are dispersed in the resin and uniformly magnetized to have programmed magnetic polarities during the printing process. Under an external magnetic actuation, the printed structures deform accordingly.

DIW is widely used for printing hard-magnetic soft actuators (11, 87–89). For example, 3D-printed programmable hard-magnetic soft actuators that enable fast transformations between complex 3D shapes via magnetic actuation have been developed (90–92). This approach is based on DIW of an elastomer composite containing ferromagnetic microparticles. Diverse functions derived from complex shape changes can be achieved, including reconfigurable soft electronics, jumping mechanical metamaterials, and soft robots that can crawl, roll, catch fast-moving objects, and transport a pharmaceutical dose. Wu et al. (93) developed biomimetic crawling and swimming robots that allow asymmetric multimodal actuation of the hard-magnetic particles. Through cooperative thermal and magnetic actuation, Ma et al. (94) demonstrated a series of pop-up designs with multiple deformation modes using a magnetic multimaterial DIW system (**Figure 7*a***). Multiple shape manipulations in one material system have been realized by embedding hard-magnetic particles in a shape-memory-polymer matrix (95) (**Figure 7*b***). Several methods have been proposed to design hard-magnetic soft active materials, such as models based on mechanics (96–98) and voxel-encoding printing guided by an evolutionary algorithm (99).

Both DLP and DIW have been used to 3D print soft-magnetic soft actuators. For example, a magnetically actuated, multimaterial, and multifunctional soft monolithic robot with biaxial locomotion capability has been 3D printed using particle–polymer composites loaded with magnetic nanoparticles (100, 101). Magnetically responsive polymer materials with tunable mechanical and magnetic properties have been DLP printed and exhibited morphing motions (102) (**Figure 7*c***). The locally programmed magnetic particle distributions are a result of its magnetic actuation intelligence, allowing several locomotion functions, such as crawling, steering, and turning. Pan's group (103, 104) developed a magnetic field–assisted DLP process to print soft magnetic robots with rotation motion and on-demand drug delivery applications. Roh et al. (105) proposed a magnetoactive soft actuator that undergoes complex reconfigurations and shape changes in an applied magnetic field. Shao et al. (106) used the DLP method to 3D print a magnetic microgripper that can operate in air and water.

Using 3D-bioprinting technologies, Tognato et al. (107) demonstrated that a nanocomposite hydrogel with complex heterogeneous structures responds to a magnetic field (**Figure 7*d***). By combining the magnetic stimulus-responsive hydrogel with the architectural control provided by bioprinting technologies, one can also create 3D structures that exhibit functionalities beyond those of native tissue. Qi et al. (108) developed an FDM printing method to print magneto-active soft materials with carbonyl iron particles embedded in a silicone rubber matrix, allowing walking, swimming, or grabbing.

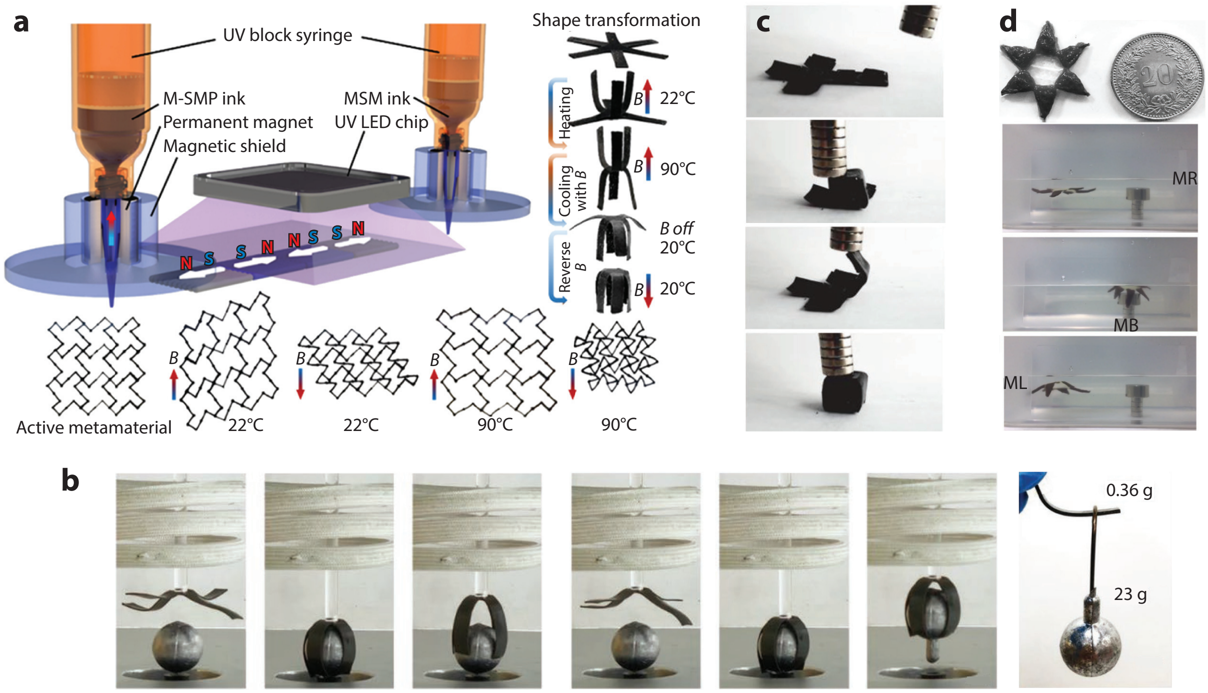


**Figure 7**

3D-printed magnetically driven soft actuators. (*a*) A series of pop-up designs with multiple deformation modes demonstrated using cooperative thermal and magnetic actuation. Panel adapted with permission from Reference 94. (*b*) Shape locking and lifting of a magnetic soft robotic gripper via superimposed magnetic fields. Panel adapted with permission from Reference 95. (*c*) Folding locomotion of magnetically driven soft actuators made with the DLP method. Panel adapted with permission from Reference 102. (*d*) Swimming and wrapping movements of a magnetic starfish made using DIW. Panel adapted with permission from Reference 107. Abbreviations: DIW, direct ink writing; DLP, digital light processing; MB, electromagnet placed on the bottom; ML, electromagnet placed on the left, MR, electromagnet placed on the right; MSM, magnetic soft material; M-SMP, magnetic shape-memory polymer.

## 3.4. 4D Printing

4D printing is a targeted evolution of the 3D-printed structure in terms of its shape, properties, and functionality (15, 109–127). Since Tibbits (128) first proposed the concept of 4D printing at a 2013 TED conference, it has generated significant interest in soft robotics. The fabrication methods for 3D and 4D printing soft robots are essentially the same. The critical difference lies in the choice of stimulus-responsive materials. Under an external stimulus, such as pH, heat, or light, the printed structures' shape, properties, or functionalities change with time. 4D printing can fabricate soft robots with self-assembly, multifunctionality, or self-repair properties.

**3.4.1. Heat-driven soft actuators.** Various 4D-printed soft actuators have been designed using the modulus change of shape-memory polymers upon temperature change (112, 129–136). For example, Ge et al. (133) used the DLP method to 3D print a soft gripper based on a multimaterial shape-memory polymer and demonstrated shape transition via thermal stimulus (**Figure 8*a***). Zhang et al. (137) used a multimaterial 4D-printing method to fabricate shape-memory-polymer structures that could later be transformed into complex 3D shapes using pneumatic input.

Inkjet is another common way to fabricate high-resolution soft actuators based on shape-memory polymers, as Vero is a shape-memory polymer that exhibits two orders of stiffness change (from ∼10 MPa to ∼1 GPa) with a glass transition temperature at ∼60°C. For example,

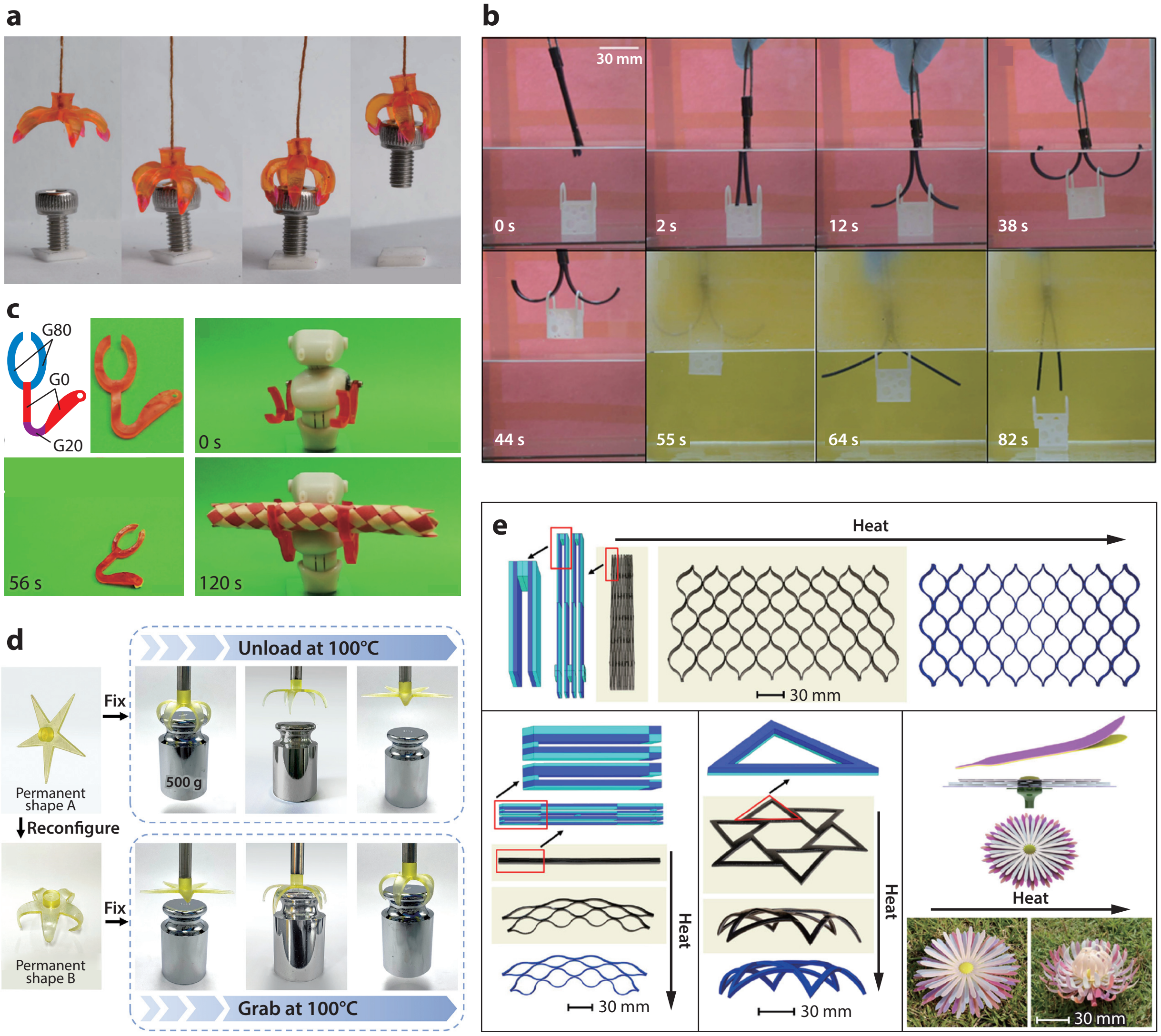


**Figure 8**

4D-printed soft actuators. (*a*) A multimaterial gripper that can grasp an object, fabricated using the DLP method. Panel adapted from Reference 133 (CC BY 4.0). (*b*) A smart structure that can bend and lift a box from water, fabricated using the inkjet method. Panel adapted from Reference 134 (CC BY 4.0). (*c*) An artificial arm that can bend, fabricated using the DLP method. G0, G20, and G80 denote the grayscale percentages used during printing. Panel adapted from Reference 141 (CC BY 4.0). (*d*) A gripper with shape reconfiguration, fabricated using the DLP method. Panel adapted with permission from Reference 142. (*e*) Direct 4D printing of structures using the inkjet method, including lattice structures, flat star-shaped structures, and printed flowers. Panel adapted from Reference 139 (CC BY 4.0). Abbreviation: DLP, digital light processing.

shape-memory-polymer-based origami airplanes, crawling insects, and soft grippers (**Figure 8*b***) have been designed (112, 131, 134). Direct ways of forming 4D-printed structures have also been demonstrated, where the structures are driven by internal stress built during the 3D printing (138–140). In a frontal photopolymerization process, internal stress is built inside the cured photopolymers due to the volume shrinkage during photopolymerization. Through selective curing using the projected geometrical pattern, one can program various actuations and shapes (140, 141) (**Figure 8*c***). Cui et al. (142) developed a DLP-printed gripper that can grab and unload via shape reconfiguration (**Figure 8*d***). Wang et al. (143) programmed different planar structures to form 3D structures via frontal photopolymerization by rationally designing the grayscale and geometric patterns. Ding et al. (138, 139) used the built-in compressive strain during photopolymerization to induce 4D shape changes in composite structures consisting of a glassy shape-memory polymer and an elastomer. Upon heating, the shape-memory polymer softens, releases the constraint on the strained elastomer, and allows the object to transform into a new permanent shape (**Figure 8*e***). Peng et al. (144) proposed a hybrid multimaterial 3D-printing method integrating DLP and DIW to 4D print active soft robots driven by liquid crystal elastomers (LCEs).

An LCE is an integration of liquid crystal mesogens and polymer networks that has attracted significant attention because of its unique actuation performance and tailorable energy dissipation behavior (145, 146). LCEs exhibit reversible actuation performance, originating from the liquid crystal–isotropic phase transition upon external stimuli such as heating. To achieve reversible actuation performance, liquid crystal mesogens should be uniformly aligned on a macroscopic scale.

DIW is often used to fabricate 3D LCE objects. Yuan et al. (147) proposed a method to realize reversible LCE actuators, in which Joule heating produced by printed conductive wires is applied to deform the LCE bar and the shape is restored after power-off (**Figure 9*a***). A morphing airplane, an origami structure, a cubic box, and a soft crawler have been designed using this method. Lewis's research group (123) used high-operating-temperature DIW of LCE inks to align the mesogen domains along the direction of the print path and demonstrated the power of this 3D-printing method via shape-morphing LCE actuators (**Figure 9*b***). By controlling the print paths, one can morph the printed planar LCE actuators into a cone or saddle shape. Lewis's research group also developed innervated LCE actuators with prescribed contractile actuation, self-sensing, and closed-loop control via core-shell DIW 3D printing (148) and, through an integrated design and 3D printing, created a double-layer LCE "rollbot" that assembles into a pentagonal prism and self-rolls in programmed responses to thermal stimuli (149) (**Figure 9*c***). Ambulo et al. (150) introduced liquid metal and a eutectic gallium indium alloy into an LCE matrix to prepare composite inks for 3D-printed soft actuators that can change shape in response to electrical power and light (**Figure 9*d***).

Recently, DLP 3D printing has been combined with liquid crystal orientation technology to obtain 4D printing of LCEs for use in actuators and soft robots. For example, Li et al. (151) reported a DLP-based additive manufacturing approach for LCEs that automatically shear aligns mesogenic oligomers with high orientational order; this method enables the fabrication of artificial muscle-like actuators that can be remotely triggered for large strokes, fast responses, and highly repeatable actuations (**Figure 9*e***). High-resolution energy-dissipative LCE devices have also been fabricated, using the inherent dissipative behavior of liquid crystal material and foam mesostructures of periodic unit cells (152, 153). Fang et al. (154) fabricated LCE artificial muscles with designable complex motion, taking advantage of the light attenuation along the thickness direction in the photo-curing process. The attenuation creates mesogen alignment, thus enabling reversible bending.

**3.4.2. Light-driven soft actuators.** Light is also commonly used as a wireless stimulus for soft actuators. Light is ubiquitous in our daily lives. Its physical parameters, such as intensity, wavelength, and polarization, can be easily tailored with high spatial and temporal resolution (155). The on-demand control techniques enable light-driven robots' versatile, sophisticated, and multifunctional motions (156). Light can trigger macroscopic deformation, an inequivalent thermal strain,

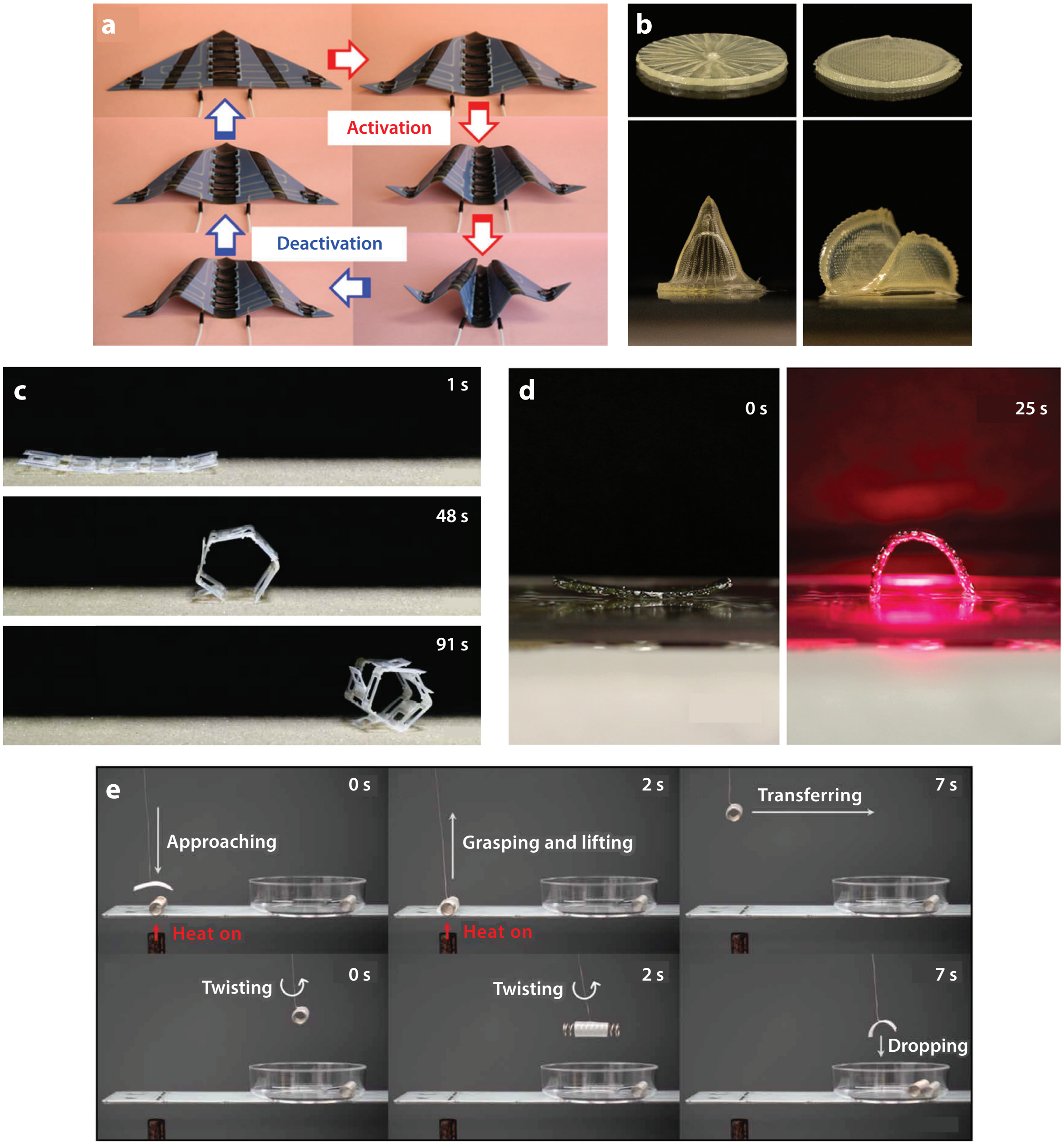


**Figure 9**

4D-printed LCE actuators. (*a*) The activation and deactivation process of an LCE airplane. Panel adapted with permission from Reference 147. (*b*) Printed planar LCE actuators that can morph into cones or saddle shapes by controlling the print paths. Panel adapted with permission from Reference 123. (*c*) Printed LCE-based self-propelling structure. Panel adapted with permission from Reference 149. (*d*) Photothermal actuation of a liquid metal–LCE strip upon irradiation with near-infrared light. Panel adapted with permission from Reference 150. (*e*) A soft robotic gripper used to grasp, deliver, and release a spring. Panel adapted from Reference 151 (CC BY 4.0). Abbreviation: LCE, liquid crystal elastomer.

water desorption, a change of hydrophobicity, a change of surface tension, a phase transition, or a change of magnetic properties.

Han et al. (157) reported a holistic artificial muscle with integrated light-addressable nodes using one-step laser printing from a bilayer structure of poly(methyl methacrylate) and graphene oxide compounded with gold nanorods. The artificial muscle can implement full-function motility without further integration and is reconfigurable through wavelength-sensitive light activation. The authors demonstrated a biomimetic robot and artificial hand that showcased functionalized control. Hagaman et al. (158) developed light-driven bimorph soft actuators via 3D-printed polysiloxane liquid crystals with pendant azobenzene groups onto commercially available Kapton polyimide thin films. The bimorph soft actuators exhibit rapid and reversible mechanical actuation upon UV light irradiation, with an entire cycle completed within seconds. Nishiguchi et al. (159) developed a multiphoton lithography 4D-printing method for a bioinspired soft actuator with a defined 3D geometry and programmed printing density. The method allows for pixel-by-pixel control of printing density in gels with a resolution of a few hundred nanometers. Photoresponsive shape-memory devices have also been 3D printed (160).

## 3.5. Other Types of Soft Actuators

Other types of actuations have also been developed, including biological actuation and combustion-powered actuation. For example, Mestre et al. (161) used a 3D-bioprinting technique to fabricate bioactuators with highly aligned myotubes (**Figure 10*a***). Chan et al. (162, 163) used a 3D SLA printer to build multimaterial biological soft actuators consisting of a biological bimorph cantilever as the actuator and a base structure to define the asymmetric shape for locomotion. Contractile cardiomyocytes actuate the biobot, and 3D SLA printing can facilitate the design of the structure. The maximum recorded velocity of the biobot is ∼236 μm s$^{-1}$, with an average displacement per power stroke of ∼354 μm and an average beating frequency of ∼1.5 Hz. Raman et al. (164) demonstrated a millimeter-scale biological machine with an SLA 3D-printed skeleton. Bartlett et al. (165) used the inkjet method to 3D print a combustion-powered soft

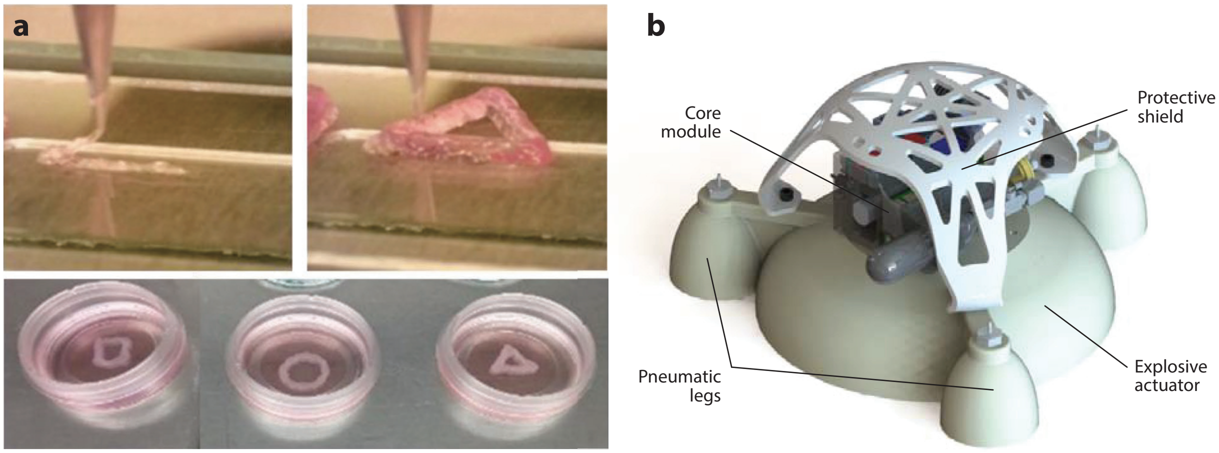


**Figure 10**

3D printing of other types of soft actuators. (*a*) 3D printing of bioactuators through DIW. Panel adapted with permission from Reference 161. (*b*) A combustion-powered jumping robot that was inkjet printed from multiple materials to create mechanical gradients that enable the robot to survive without shattering. Panel adapted with permission from Reference 165. Abbreviation: DIW, direct ink writing.

actuator whose body transitions from a rigid core to a soft exterior. 3D printing enabled a stiffness gradient spanning three orders of magnitude in its modulus (**Figure 10*b***), which reduced stress concentration and helped create a reliable interface between rigid driving components and the primarily soft body.

### 3.6. Integrated Soft Actuators and Sensors

The advantages of 3D-printing technologies provide the opportunity to integrate a network of actuators, sensors, and control and power modules into fully autonomous soft robots through a single, on-demand digital fabrication process. The systematic integration can facilitate robotic manipulation and locomotion with precise closed-loop control and promote the mechanical intelligence of soft robots.

Wehner et al. (166) used a multimaterial embedded 3D-printing technique to develop an untethered robot composed solely of soft materials. The robot is actuated by gas generated from fuel decomposition and controlled with a microfluidic logic that autonomously regulates fluid flow. The authors applied this approach to engineer a multimaterial Octobot that can pneumatically raise its individual tentacles. Truby et al. (167) employed the same 3D-printing technique to create soft actuators with multiple sensing capabilities (**Figure 11*a***). The fabrication method enables the seamless integration of pneumatic structures with sensing components, including curvature, inflation, and contact sensors. The demonstrated soft grippers could simultaneously provide haptic, proprioceptive, and thermal sensing feedback when grasping objects. Using the SLS technique, Scharff et al. (168) demonstrated a 3D-printed soft robotic gripper that integrates actuators, sensors, and structural components. The FDM technique has also been used to develop soft actuators with tactile sensing enabled by complex 3D-printed structures (169–172). Ntagios et al. (169) designed a biomimetic hand embedded with soft capacitive sensors that can detect pressure (more than 1 kPa) (**Figure 11*b***). They combined an FDM printer with a second nozzle for paste/ink extrusion, capable of printing conductive ink, metal paste, and polymers. Similarly, Sadeghi et al. (173, 174) developed a bioinspired robot that creates its own body through an FDM process and integrates with a sensorized tip (**Figure 11*c***). The actuator can grow with a speed of up to 4 mm $\mathrm{min}^{-1}$, overcoming medium pressure of up to 37 kPa and bending with a minimum radius of 100 mm. Zhu et al. (175) developed a hydrogel microfish using a DLP 3D-printing method with toxin sensors that exhibit chemically powered and magnetically guided propulsion. Shen et al. (176) further fabricated a conducting polymer hydrogel strain sensor through DIW, which enabled the proprioceptive sensing of a pneumatic actuator. The inkjet method has also been used to print multimaterial soft robotic fingers with self-powered triboelectric curvature sensors (177).

## 4. PROGRESS AND PERSPECTIVES

Despite the significant progress in the field of 3D printing for soft robotics, its further development requires the development of novel 3D-printable soft materials, advanced 3D-printing technologies capable of efficient and rapid deposition of multiple materials, and computational design tools incorporating realistic material models to predict the actuation behaviors of the 3D-printed soft robots. This section discusses integrated 3D printing, multiscale 3D printing, 4D printing, and other novel printing methods, such as voxel printing and one-step volumetric 3D printing.

### 4.1. Multiscale 3D Printing

Nature has developed high-performance biostructures over millions of years of evolution and has become an important inspiration source for designing high-performance materials and

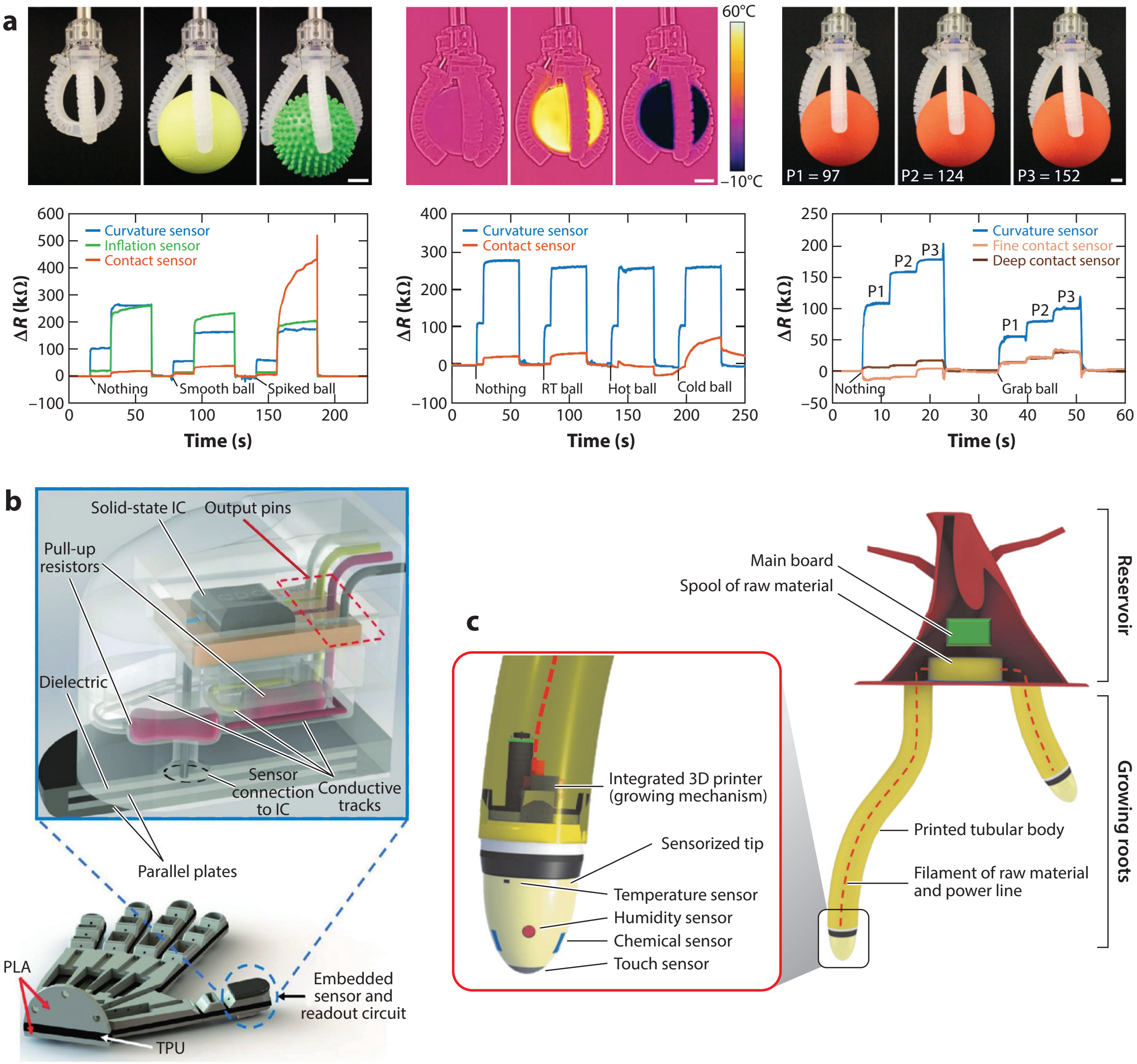


**Figure 11**

Integrated soft actuators and sensors. (*a*) Embedded 3D-printed soft actuators with somatosensitive capabilities. Panel adapted with permission from Reference 167. (*b*) A 3D-printed robotic hand with soft tactile capacitive sensors. Panel adapted from Reference 169 (CC BY 4.0). (*c*) Plant-inspired robots that use multiple tip sensors and an FDM printer to sense their surroundings and selectively grow to avoid obstacles. Panel adapted with permission from Reference 174. Abbreviations: FDM, fused deposition modeling; IC, integrated circuit; PLA, polylactic acid; RT, room temperature; TPU, thermoplastic polyurethane.

structures. Multiscale structure is an essential property of biological materials that can improve their characteristics.

The ability to fine-tune functional material properties by incorporating nanomaterials in 3D printing offers an attractive approach to achieving seamless multifunctional integration. One way to fabricate nanoscale structure is by two-photon polymerization, with as small as 9-nm voxel resolution. Another way is to use patterning phenomena in 3D printing to create nanoscale structures, such as shear, evaporative, acoustic, electrical, magnetic, optical, or thermal phenomena.

Two-photon polymerization is a powerful 3D precision nanofabrication method where polymerization is initiated by two-photon absorption with a pulsed infrared laser. It has been extensively applied to fabricating microscale and nanoscale soft actuators. For example, Ma et al. (178) reported femtosecond laser-programmed artificial musculoskeletal systems for prototyping 3D microbots, using relatively stiff SU-8 as the skeleton and pH-responsive protein (bovine serum albumin) as the smart muscle. They also proposed a two-photon polymerization method to enable the sequential structuring of two photosensitive materials within a predesigned configuration. Zeng et al. (179) reported a microscopic walker able to move on different substrates in a dry environment, consisting of LCE as the muscles and four conical legs made using an IP-Dip photoresist.

Fabricating multiscale 3D structures at high resolution is challenging, especially for mechanically weak hydrogels. To 3D print multiscale and multimaterial hydrogel structures with microscale resolution, Kunwar et al. (180) developed a hybrid laser-printing technology. Multiscale hydrogel fractal bionic channels can be printed by moving the convex lens of a DLP-based 3D-printing system (181). A microscale piezoelectric nanoactuator has been printed using the microscale DLP method (182).

Another advantage of multiscale printing is its ability to improve the global print speed with the desired local resolution. Li et al. (183) proposed a multiscale SLA method realized by dynamic switching of laser spot size and adaptively sliced layer thickness. Using different slicing and printing settings for different portions, they printed macroscale objects with microscale surface structures and showed a significant improvement in the global printing speed.

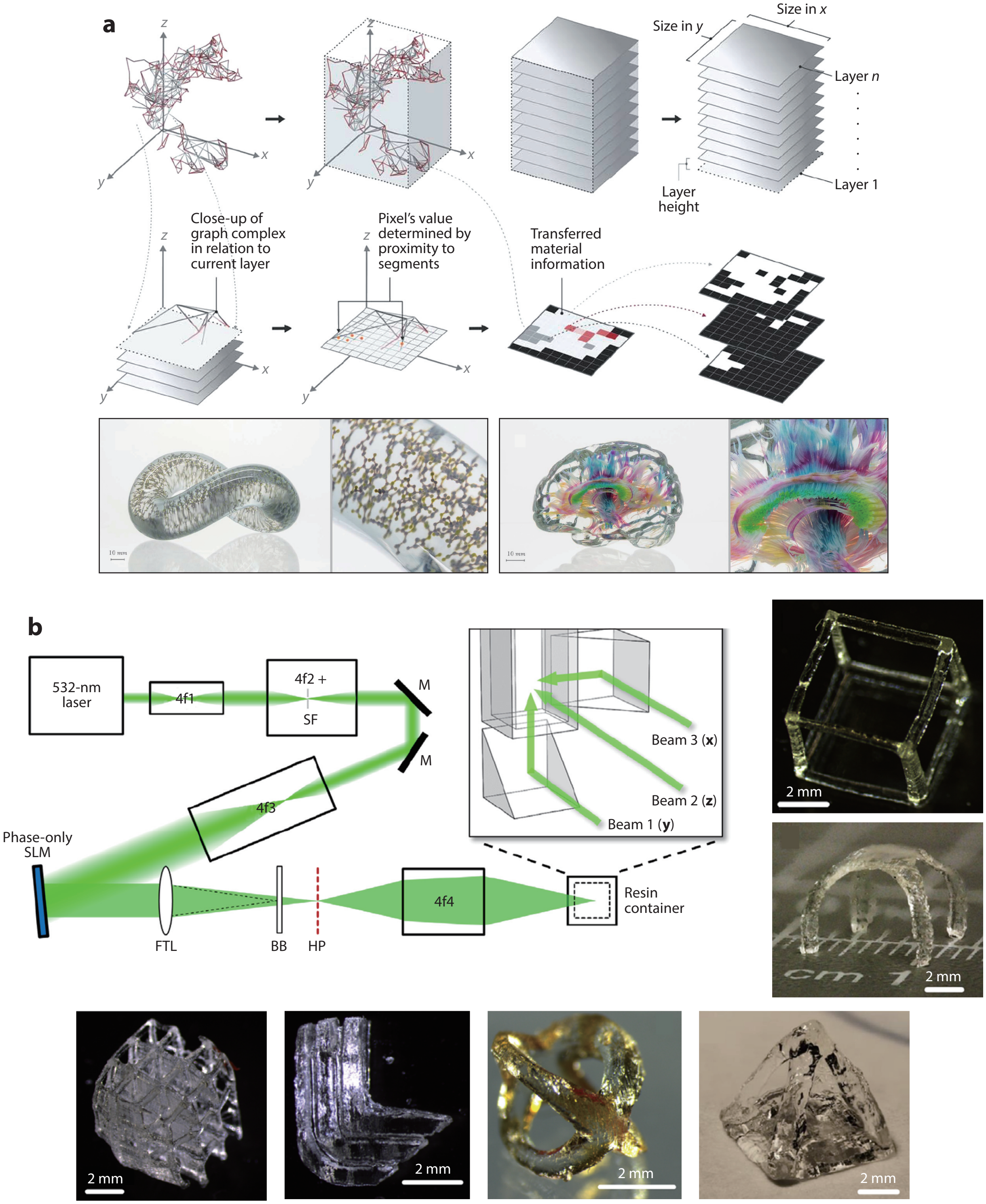
## 4.2. Novel Printing Methods

Multimaterial voxel printing is needed for fabricating soft robots with complex functions. Bader et al. (184) presented an approach to physical data visualization through voxel printing using multimaterial 3D printing to improve the current data physicalization workflow (**Figure 12*a***). Multimaterial 3D printing with photopolymeric materials enables the simultaneous use of several different materials. Full-color models with variable transparency can be created using dedicated cyan, magenta, yellow, black, white, and transparent resins.

Skylar-Scott et al. (185) recently proposed a multimaterial, multinozzle method that can design and fabricate voxelated soft matter. The material's composition, function, and structure are programmed at the voxel scale. Compared with the inkjet-based 3D-printing method, where only a few materials can be chosen, DIW is used to pattern a much broader range of materials. Multimaterial voxel printing also enables the design of soft actuators (186–189). Boddeti et al. (187, 189) demonstrated a workflow that digitally integrates design automation, material compilation, and digital fabrication via voxel-based additive manufacturing with material jetting of multiple photocurable polymers.

Low speeds and geometric constraints in 3D printing are two limitations in fabricating soft robots. Both limits are overcome by a one-step volumetric additive manufacturing method for complex polymer structures (190) (**Figure 12*b***). Through the use of holographic patterning of a light field, various structures can be successfully built in ∼1–10 s. In DLP 3D printing, precision and speed are limited by the vertical adhesion of in situ cured resin at the curing interface. Wu et al. (191) developed an ultra-low-adhesive interface to overcome the unavoidable adhesion and improve printing precision and speed.

To fulfill the requirement that many applications require integrating different materials and multiple 3D-printing technologies, Roach et al. (192) developed a novel multimaterial,



(*Caption appears on following page*)

**Figure 12** (*Figure appears on preceding page*)

Novel 3D-printing methods. (*a*) A curve and graph data-processing workflow for voxel printing and representative 3D-printed models. Panel adapted from Reference 184 (CC BY 4.0). (*b*) A holographic volumetric 3D fabrication system schematic and example structures. Panel adapted from Reference 190 (CC BY 4.0). Abbreviations: 4f*N*, telescope lens pairs used for beam expansion or image relaying; BB, beam block to eliminate undiffracted light; FTL, Fourier transform lens; HP, hologram plane; SF, spatial filter; SLM, liquid crystal on silicon spatial light modulator.

multimethod 3D printer comprising multiple 3D-printing technologies. Four 3D-printing technologies and two complementary technologies—inkjet, FDM, DIW and aerosol jetting, along with a robotic arm for pick and place and photonic curing for intense pulsed light sintering—are combined onto one platform.

## 5. DISCUSSION AND CONCLUSION

In this article, after a brief introduction of various 3D-printing methods, we reviewed 3D-printed soft robots according to their actuation methods. We then discussed the integration of actuators and sensors, followed by advanced 3D-printing technologies (such as multiscale and multimaterial 3D printing) and perspectives on 3D-printing technologies. 3D printing enables the fabrication of multimaterial, multiscale, and multifunctional soft robots. The further development of 3D printing for soft robotics will require overcoming the challenges of realizing multimaterial, multiscale, and multifunctional properties (**Figure 13**):

1. Multimaterial: The human finger consists of many different parts, such as fat (Young's modulus of ~2 kPa), skin (~30 MPa), muscle (~500 MPa), joints (~750 MPa), nail (~1 GPa), tendon (~1 GPa), and bone (~20 GPa), which enable its dexterous and stiffness-tunable motions (**Figure 13**). Mimicking these properties in fabricated soft fingers requires multimaterial 3D-printing methods, but the currently available 3D-printing technologies still face various limitations regarding resolution, speed, and material compatibility. The materials used in SLS and FDM are restricted mainly to thermoplastic materials, which are unlikely to meet the advanced material demands for highly resilient functional components. DIW can be used for multimaterial printing, but the material has to solidify after flowing through the nozzle, and the bonding between different layers in DIW is not tight enough. Inkjet enables rapid multimaterial printing, but the materials are limited due to the requirement of low viscosity, and currently, the commercial elastomers generally cannot exceed 200% strain. DLP 3D printing can realize covalent bonding between different polymers, but available materials are limited. The development of new materials and the studies on bonding mechanisms can significantly promote multimaterial 3D printing.
2. Multiscale: Many natural organisms exhibit remarkable designs, with building blocks hierarchically arranged from nanometer to macroscopic length scales. Different scales can provide different mechanical properties. For example, in a hexactinellid sponge, nanometer-scaled spheres are arranged to form laminated spicules to increase the fracture strength (193) (**Figure 13**). The assembly of these spicules into bundles and the formation of cylindrical square-lattice structures are reinforced by diagonal ridges at the macroscopic scale, which provide the highest buckling resistance. 3D printing enables the integration of multiscale designs in a single structure. However, 3D printers that can fabricate structures across multiple scales are currently lacking, due to the trade-off between speed and resolution and the need to incorporate multiscale optical design and multiscale features in one setting.
3. Multifunctional: 3D-printed soft robots demonstrate multiple functions, especially actuation and sensing. Due to the infinite degrees of freedom, nonlinear behavior, hysteresis of soft materials, complex 3D geometries, spatial distribution of multiple materials, and various

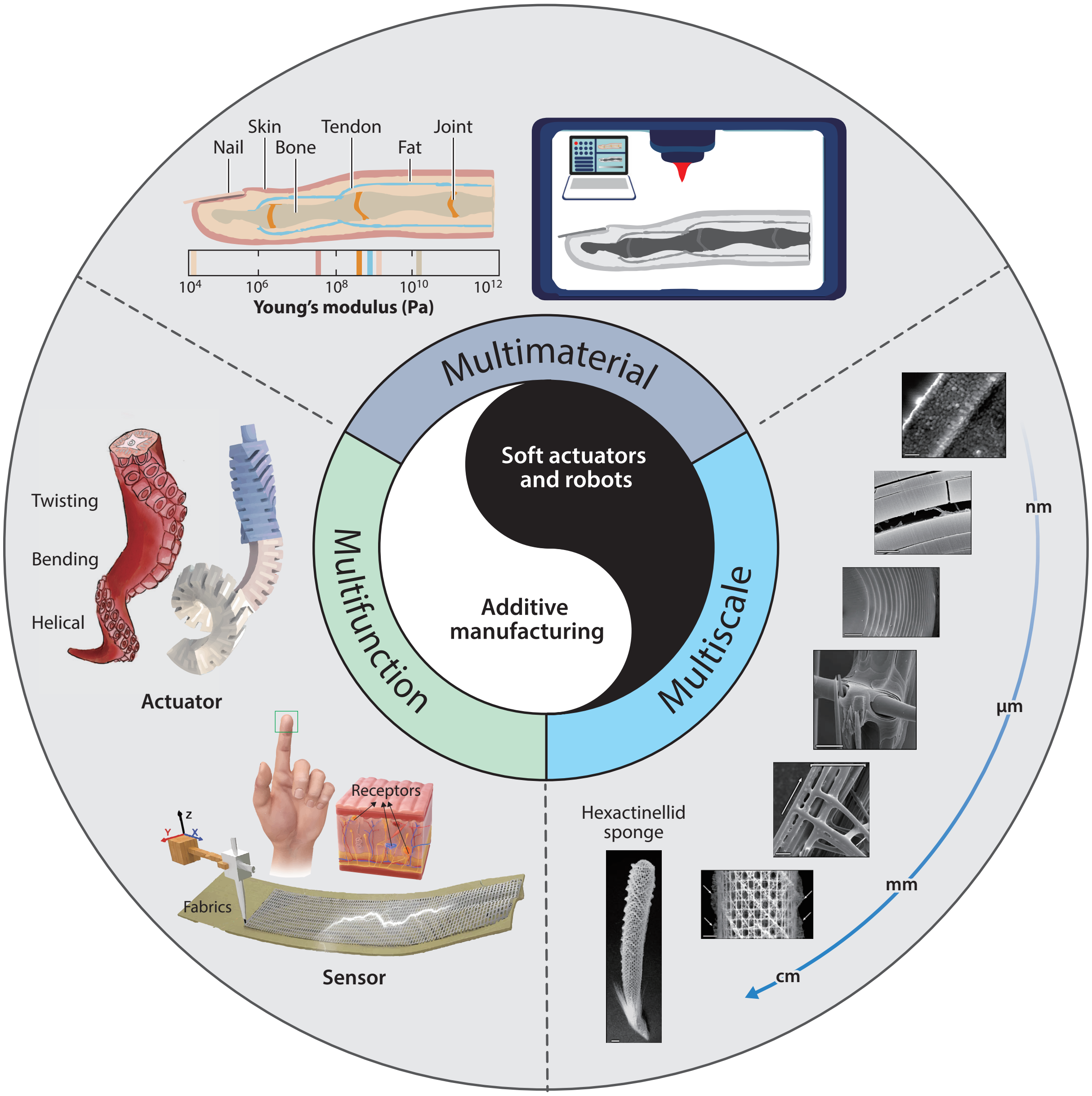


**Figure 13**

The emerging challenges of large-scale integration of multimaterial, multiscale, and multifunctional properties by 3D-printed soft robotics. Hexactinellid sponge adapted with permission from Reference 193.

actuation methods, it is still challenging to realize the controllable actuation of 3D-printed soft robots at high fidelity (189). Current soft robots have limited sensory capabilities. Implementing complex functions requires next-generation devices to detect their deformation state, applied forces, and environmental conditions. A fully autonomous soft robot requires an integrated power system to enable continuous motion. Progress in 3D printing will allow for the direct printing of soft robots with distinct functional components.

Soft materials are elastic and can deform with an infinite number of degrees of freedom, making control tasks very challenging. Controlling soft robots requires new approaches to modeling, control, and dynamics. To automatically design the complex 3D trajectories of pneu-net soft manipulators, Jiang et al. (194) developed a methodology that can match complex 3D trajectories upon a single pressurization. The 3D motions can be characterized by twisting, bending, and helical deformations, which are enabled by the design of soft segments with programmable chamber orientations. Huang et al. (195) proposed a variable-curvature kinematic modeling approach for soft continuum robots, achieving both accurate motion simulation and feedforward control based on an absolute nodal coordinate formulation. To design 4D-printed soft robots, structure design and the nonlinear behaviors of soft smart materials should be considered. Recently, theoretical models have been developed to predict the programmable shape changes of the 3D-printed soft actuators by incorporating the complex geometries and nonlinear behaviors of the active materials as well as diverse external stimuli (196–201).

Although 3D-printing technology provides manufacturing freedom and promising possibilities for individualization without adjusting production machines, the 3D-printed objects need to meet industrial standards to further expand the applicability of 3D printing in various industrial areas. For example, a variety of 3D-printed upper-limb prostheses have been developed owing to the promising possibility of producing complex geometries and custom and personalized designs combined with ease of manufacturing. However, to compete with or replace prostheses manufactured by conventional methods, 3D-printed prostheses should improve on their functions, mechanical properties, durability, comfort, fabrication accuracy, available materials, and size. Gu et al. (202) recently developed a soft, low-cost, lightweight (292 g) neuroprosthetic hand that provides simultaneous myoelectric control and tactile feedback. This hand not only outperforms conventional rigid neuroprosthetic hands in speed and dexterity but also can help an individual with a transradial amputation regain primitive touch sensation and real-time closed-loop control. The proposed manufacturing and design method paves the way for developing the next-generation soft hand.

The field of 3D printing of soft actuators and robots is still new. Demand for 3D-printing technologies will increase due to their capability to customize application-specific and defect-specific needs. Integrating all critical points mentioned and finding solutions to cope with the challenges are essential for achieving autonomous soft robots.

## DISCLOSURE STATEMENT

N.X.F. is a cofounder of Boston Micro Fabrication, which manufactures high-precision micro–3D printers and provides 3D-printing services.

## ACKNOWLEDGMENTS

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