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Recent Advances in Electrically Driven Soft Actuators across Dimensional Scales from 2D to 3D

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Soft actuators have been an important research focus in robotics due to their advantages in nondestructive contact and excellent motion adaptability, which enable flexible manipulation, extreme environments exploration, and in vivo surgical treatment. Various soft robots actuated electrically, magnetically, optically, and fluidically are built toward different application scenarios. Among them, electrical actuation method is an advanced choice to actuate and control soft actuators that are expected to be compatible and integrated with existing industrial robotic systems and wearable intelligent devices. Current robotic systems have higher requirements on the actuators' function, which can be explored through material and structural designs. Based on a variety of deformable materials, the structural design enables the soft actuators to span from low dimension to high dimension with further improvement in function. Therefore, in this review, 2D and 3D electrical-based soft actuators from the perspective of dimension design are introduced, which involve functional materials, structure design, and fabrication technology. Some novel 3D fabrication methods, such as the 3D compressive buckling process, are summarized to build 3D soft robots. This review aims at offering important guidelines for the development of soft actuators and the construction of integrated robotic systems in the future.

1. Introduction

Robot, as an automatic device, can conduct many production tasks to save labor costs.[1] For example, industrial robotic arms and manipulators can carry out industrial and agricultural production, including cargo handling and high-precision industrial operations.[2] Further, robot can also accomplish tasks that humans cannot do by hand.[3,4] Specifically, the Da Vinci robot could assist people to perform high-precision minimally invasive clinical surgery,[5,6] and microrobots could enter blood vessels or organs for drug delivery and miniaturized soft robots could perform healing tasks in human organs such as the stomach and intestines.[7–11] Therefore, considering its irreplaceable role, robotics will be one of the development focuses of the future science and engineering field. In the field of robotics, soft robot is a good choice for both industrial manipulation of fragile objects and in vivo biomedical applications[12] because they do not cause sharp damage to the objects they touch and can also pass through the in vivo environment via adaptive arbitrary deformation.[13]

Soft actuators are the basic components to build soft robots.[14,15] Soft actuators can be divided into magnetic,[16] optical,[17] fluidic,[18,19] electrical,[20] and other driven method-based devices, according to different actuation modes. Given the fact that magnetic fields can pass through body tissues almost lossless and have abundant programmable control properties, magnetic actuation is very suitable for the development of biomedical robots.[21] Magnetic soft robots is capable of in vivo crawling, rolling, rotating, and grasping or transporting objects based on 3D structural deformation,[22,23] benefiting from diversified magnetic field distribution control. However, programmable magnetic field control often requires a complex magnetic control system, and the magnetic field will weaken a lot at a long distance. Therefore, magnetic control is more suitable for wireless robot control at close range. For remote wireless actuation and control, optical control is a good alternative, because the laser can maintain high energy in the long-distance propagation. Under optical actuation, the deformation of the soft actuators comes from the absorbed high-energy light by the deformed material.[24] As a result, light-driven soft robots can exhibit excellent motion characteristics, but the soft actuators are difficult to operate or carry heavy loads because the light-induced deformation is not strong enough. In this regard, fluid-driven robots tend to exhibit large deformations and forces powered by high pressures based on external air currents or water flows.[25,26] Therefore, the fluidic soft actuators are typically used in industrial operations such as object grasping and handling.[27] However, fluidic soft actuators

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also require air or liquid pumps connected with soft piping,[28] and it is very difficult to make wireless fluidic soft robotic systems, both of which limit their biomedical applications.

For electrical soft actuators, it is easy to realize the wireless actuation via battery or radio-frequency power supply technology.[29] The soft piezoelectric and dielectric materials can generate specific deformation under certain voltages, and many organic materials show obvious thermal expansion under electric heating, all of which can be used to develop electrical soft actuators. More importantly, the control of the electric soft actuators is very simple relying only on the power supply to the designed control circuits. Specifically, electrical actuation and control has the following innate advantages: 1) The electrical soft actuator is more compatible with the current industrial robot system. Systematic integration of robots can be achieved by power supply alone without the need for additional magnetic, optical, or air pump systems; 2) Electrical soft actuator can be easily integrated with current wearable flexible systems[30] to assist specific intelligent sensing,[31–35] feedback, and actuation;[36–41] 3) The electrical soft actuator or robot is capable of sensing and wireless transmission of physiological signals,[42] which will be an important development trend of in vivo biomedical soft robot. Considering the advantages of electrical driven actuators, many researchers have published review articles to comprehensively describe electrical soft actuators from the perspective of materials, for example, electrically driven polymer-based flexible actuators,[43] low-voltage soft actuators based on electrochemical, electrothermal, and other electrical mechanisms,[44] electrically driven liquid crystal network actuators,[45] etc. Different from these previous review articles, we will not only analyze and summarize the latest research progress from the perspective of materials, but also from the perspective of actuators' dimensional design, and will also introduce some new 3D fabrication methods for 3D electrical actuators.

At present, the construction of electrical soft actuators is carried out from two aspects: material preparation and structure design. As shown in **Figure 1**, many functional materials, including organic piezoelectric materials, dielectric elastomers, liquid crystal elastomers (LCEs), and layered nanomaterial films, have been used to develop electrical soft actuators and robots. In addition to material selection and optimization, structural design is another method that can greatly improve the function of actuators and robots. 2D robots constructed by 2D actuation often exhibit crawling and other walking modes, but the deformation is too simple to perform complex tasks. Therefore, the design and construction of 3D robots are urgently needed to enhance the robot's movement and functionality. Many fabrication processing and structural design methods have been introduced to create 3D robots, such as 3D printing,[46] origami,[47–49] and the new 3D compressive buckling process[50] (Figure 1). To comprehensively present electrical soft actuators, in this review, we summarized the material design and actuation principle of 2D actuators, taking the dimension as the main line, and then introduced the 3D actuators and robots from the perspective of structural design and preparation process.

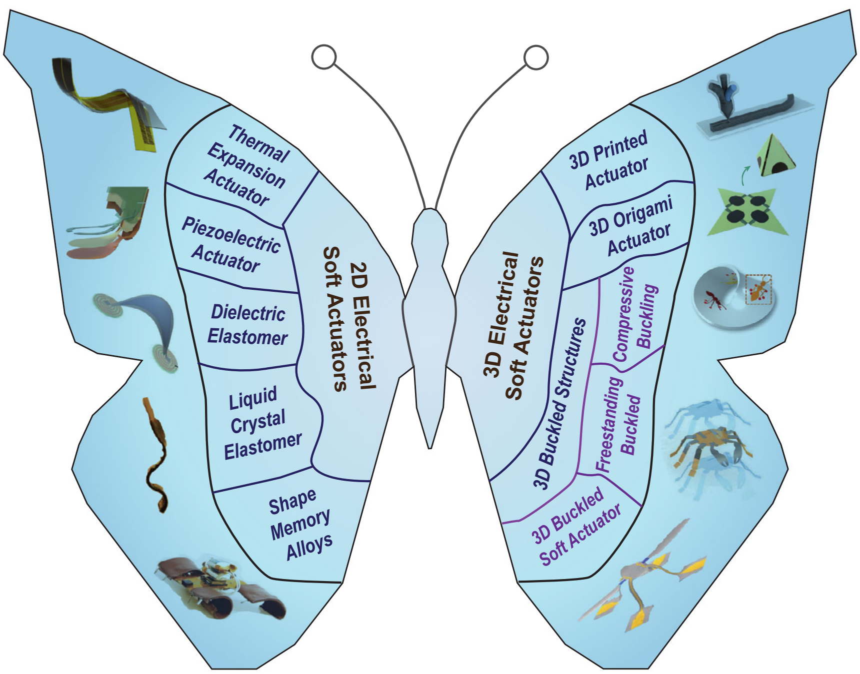

Figure 1. Summary diagram of electrically driven soft actuators across dimensional scales from 2D to 3D. Reproduced with permission.[68] Copyright 2021, Wiley. Reproduced with permission.[86] Copyright 2021, AAAS. Reproduced with permission.[94] Copyright 2018, AAAS. Reproduced with permission.[119] Copyright 2018, Wiley. Reproduced with permission.[133] Copyright 2019, Wiley. Reproduced with permission.[156] Copyright 2021, Wiley. Reproduced with permission.[181] Copyright 2022, Springer Nature. Reproduced with permission.[204] Copyright 2022, AAAS. Reproduced with permission.[211] Copyright 2022, AAAS. Reproduced with permission.[220] Copyright 2018, AAAS.

2. Soft Robots Based on 2D Electrical Soft Actuators

Most electrical soft actuators are thin films in shape that are actuated and controlled in a flat or a single dimension. We define them as 2D electrical soft actuators. These soft actuators often bend to a curved shape or twist into a helical structure. When several 2D soft actuators are assembled together, a 3D soft robot system could be built. In this part, we summarize the 2D electrical soft actuators from the perspective of materials and actuation principles. The 2D electrical soft actuators based on the electrothermal, piezoelectric, dielectric materials, LCEs, and shape memory alloys (SMAs) are described as follows.

2.1. Thermal Expansion-Based Soft Actuators

Thermal expansion-based soft actuators have attracted plenty of attention due to their advantages in wide material selection, simple manufacturing procedure, and low actuation voltage.[51–54] A typical thermal expansion-based soft actuator always contains two layers of materials that show great differences in coefficient of thermal expansion. When the soft actuator is heated, the layer with a higher coefficient of thermal expansion will expand more than the layer with lower coefficient of thermal expansion. For this bilayer actuator, the difference in expansion between two layers could induce a bending deformation. Based on this deformation mechanism, an electrical electrode as a heater can be integrated in the actuator[55,56] or one deformation layer with better conductivity can also act as the heater[57,58] to create the thermal expansion-based soft actuators.[59–63]

The heating electrodes of the soft actuators also need to be flexible with very low deformation stress, for the purpose of producing a minimum degree of stress resistance to the deformation of the actuator. To realize the electrical heating electrode with excellent flexibility, thin-film electrodes with a special structure design can be introduced.[44,64] Thin thickness can improve the flexibility of the materials, and special structural designs such as the serpentine structure, fractal pattern, and wavy pattern can further improve the mechanical properties and robustness of the materials.[65–67] A representative work associates with the report of an ultrathin actuator with thermal-responsible soft polydimethylsiloxane (PDMS) as the main body, polyimide (PI) as the substrate, and a gold electrode as the heater.[68] PDMS has a higher coefficient of thermal expansion than that of the PI layer. Therefore, when the external voltage was on, the actuator was heated and deformed. This kind of actuator was able to imitate the tongue of reptiles to hunt moving prey, and the vines wind around the objects tightly (**Figure 2**a).

In addition to flexible electrodes, conductive nanomaterial composite is also an ideal candidate as the heater of the thermal expansion-based soft actuator. Li et al.[69] developed a high anisotropic flexible carbon nanotube buckypaper as a flexible heater and a PDMS layer as a substrate. The coefficients of thermal expansion of carbon nanotube buckypaper and PDMS are quite different, which results in the significant deformation of the thermal expansion-based soft actuator. The soft actuator realized various controllable movements due to the exquisite graphic structure design and even could mimic human-hand action (Figure 2b). Besides carbon nanotube, MXene is a typical conductive nanomaterial with excellent electrical conductivity, thermal conductivity, and photothermal conversion. Cai et al. proposed a bilayer film composed of MXene–cellulose composites and polycarbonate based on the sophisticated structure of leaves (Figure 2c).[70] The MXene–cellulose composites showed a smaller coefficient of thermal expansion and larger hygroscopic expansion coefficient compared to the polycarbonate film. The synergistic effect of thermal and hygroscopic expansion resulted in outstanding actuation and deformation performance.

2.2. Piezoelectric Soft Actuators

Piezoelectric-based actuators are very unique force-generation devices that can transfer electrical energy to mechanical force, which is also called the inverse piezoelectric effect. When a piezoelectric material is applied by a specific electric field, it will generate mechanical deformation or mechanical pressure in a specific direction.[71–73] As shown in **Figure 3**a, as the piezoelectric film expands or contracts, the bilayer soft actuator bends to the plastic and piezoelectric film layers, respectively. Recently, the piezoelectric actuator has been attracting much attention in building soft robots due to its advantages of high precision, quick response, high actuation frequency, and lightweight.[74,75]

To develop a high-performance piezoelectric actuator, the piezoelectric layer should be flexible. Currently, many intrinsic flexible piezoelectric materials have been utilized, for example, poly(vinylidene fluoride) (PVDF),[76–78] polyureas,[79,80] polypeptides,[81,82] and other piezoelectric polymers.[75,83] Even though the piezoelectric coefficient of the organic piezoelectric material is relatively lower than traditional rigid piezoelectric ceramic,[84] the organic piezoelectric material is still a relatively excellent choice due to its good flexibility and easy preparation characteristics. Wu et al.[85] made use of flexible material PVDF to develop an insect-level soft robot, which ran very quickly with a speed of 20 body lengths per second (Figure 3b). Further, Liang et al.[86] added two electrostatic footpads on the basis so that the soft robot can achieve good directional controlled motion (Figure 3c). With the piezoelectric film as the main body, it can move agilely in the maze. By carrying the gas sensor, it has great application potential in gas leakage detection.

Based on the rigid piezoelectric materials, it is still possible to develop the piezoelectric soft actuators through the advanced structural design. Liu et al.[87] proposed a millirobot that was composed of three piezoelectric segments based on the segmented features of natural arthropods (Figure 3d). The millirobot was actuated by the friction between the driving feet and the operating substrate. This soft robot performed both linear motion (forward or backward) and steering and rotational motions by adjusting the voltages and phase shift of the piezoelectric leg. Moreover, this soft robot owned the same speed and agility as a centipede. The speed of this millirobot could be adjusted in the range of 516.3–0.26 $mm\,s^{-1}$ by adjusting the pulse repletion rate and the duty cycle coefficient.

Due to its fast response and high actuation frequency, rigid piezoelectric materials are also ideal for the development of small aircraft. The wings of the aircraft can be actuated by the

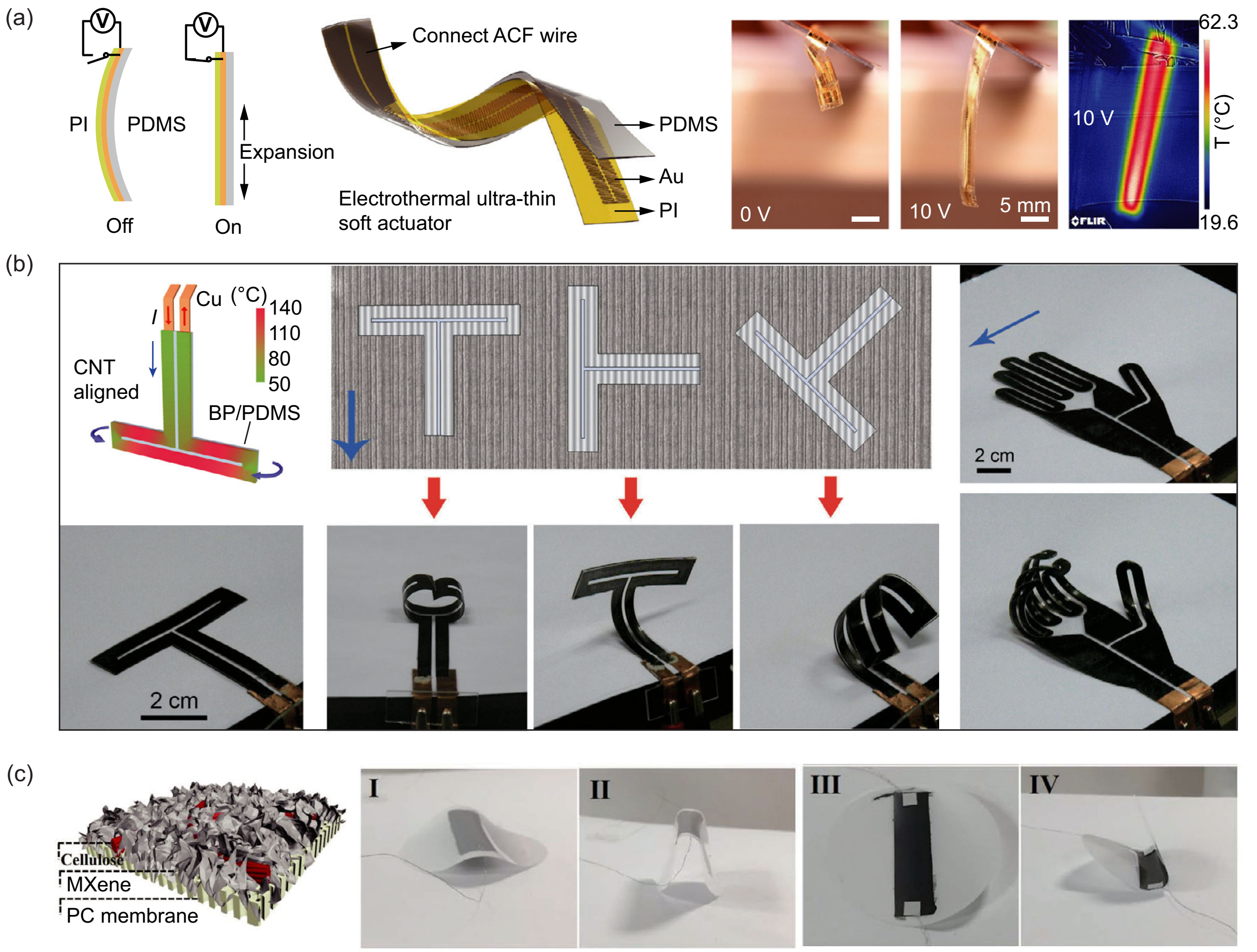

Figure 2. Thermal expansion-based soft actuators. a) Ultrathin actuator with thermal-responsible soft silicon, polydimethylsiloxane (PDMS) as the main body, polyimide (PI) as the substrate, and a gold electrode as the heater. Reproduced with permission.[68] Copyright 2021, Wiley. b) Flexible carbon nanotube paper as a flexible electrode and a PDMS layer as a thermal expansion-based soft actuator. Reproduced with permission.[69] Copyright 2015, ACS. c) The thermal expansion actuator based on MXene as the flexible electrode and a PC layer as a substrate. Reproduced with permission.[70] Copyright 2019, AAAS.

piezoelectric actuator through the designed joint in the aircraft. The high-frequency large swings of the wings allow the aircraft to fly in the sky. Jafferis et al.[88] developed an insect-sized flapping-wing aerial vehicle driven by two alumina-reinforced piezoelectric actuators to address these challenges (Figure 3e). Compared to the electromagnetically driven insect-inspired flapping-wing robot,[89] the piezoelectric actuated aerial vehicle was more lightweight. Integrated with electronics, a photovoltaic array, and a signal generator, the whole system only weighed 259 mg, which allowed additional payload capacity. Moreover, the energy consumption was about only 110–120 mw. Piezoelectric-based actuator has gained significant attention in soft robotic field due to their excellent electromechanical properties. However, the disadvantages are also obvious, such as low deformation amplitude and high actuation voltage. In the future, the wireless strategy and the development of low-voltage piezoelectric materials will be the focus of research for piezoelectric soft actuators.

2.3. Dielectric Elastomer-Based Soft Actuators

The dielectric elastomer actuator shows great application potential in develop soft robots benefiting from its advantages of lightweight, high flexibility, and low cost.[90–92] The typical dielectric elastomer actuator is composed of a dielectric elastomer layer and two compliant electrodes. When an external electric field is applied on the dielectric elastomer actuator, the electrostatic attraction between the opposite charges of the two electrodes generates electrostatic stress or pressure on the dielectric elastomer film. Then, the thickness of film decreases while the area of the film is enlarged.[93] Based on this deformation principle under high voltage, many dielectric elastomer-based soft actuators have been reported.

Gu et al.[94] reported a tethered wall-climbing robot based on dielectric elastomer actuator (DEA) as the moving body and the electroadhesive feet to give adhesion on the wall, which can

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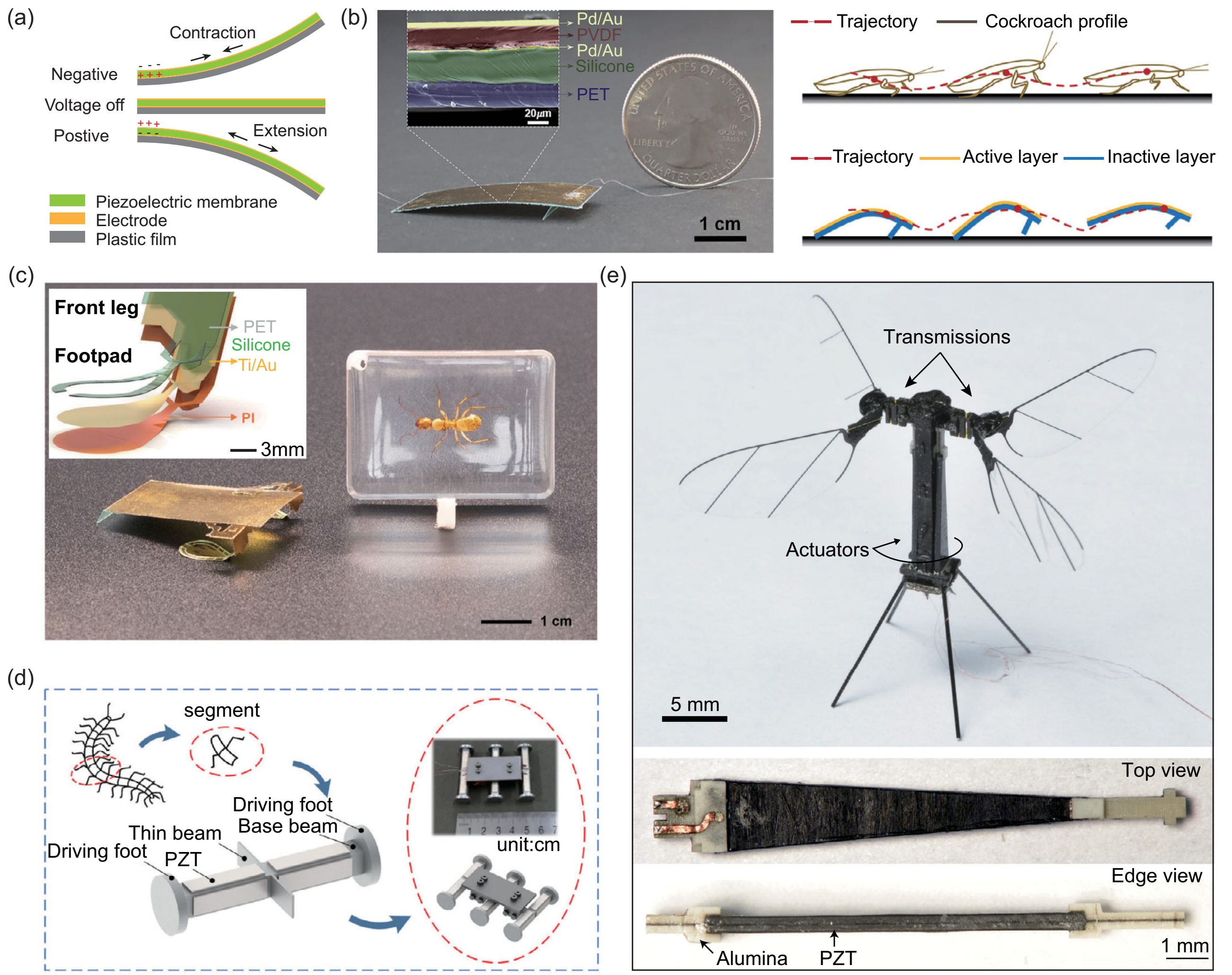

Figure 3. Piezoelectric soft actuators. a) Mechanism of piezoelectric-based actuators. b) Insect-level soft robot actuated by piezoelectric effect. Reproduced with permission.[85] Copyright 2019, AAAS. c) A piezoelectric actuator-based soft robot that can realize the rotating motion by electrostatic footpads. Reproduced with permission.[86] Copyright 2021, AAAS. d) Piezoelectric-actuated soft robot with features of natural arthropods. Reproduced with permission.[87] Copyright 2021, Wiley. e) Insect-sized flying robots realized by piezoelectric actuators. Reproduced with permission.[88] Copyright 2019, Springer Nature.

achieve a 90° climbing on the wood, paper, and glass walls with speed of up to 0.75 body length per second. When carrying the camera with visual feedback in a vertical tunnel, the robot can adjust its body to through a narrow place and a maze-like planar track (**Figure 4**a). Based on more advanced designs, the dielectric elastomer actuator-based soft robot can not only move on land but also swim in the sea or fly in the sky.[95–98] All of these soft robots show great application potential in exploring places where a human finds it difficult to reach. Li et al.[99] developed a manta ray-inspired dielectric elastomer actuator-based soft electronic fish with encapsulated hydrogel as one conductive electrode and surrounding tap water as another electrode (Figure 4b). Interestingly, the surrounding water as electric ground could further improve the safety and stability of the device. The muscles and body of fish remained at rest under no voltage state. When a voltage was applied, positive and negative charges accumulate on both sides of the dielectric elastomer and cause deformation for robotic actuation. Based on this mechanism, it performed a swimming motion at a speed of 0.69 body length per second with a 3 h long operation term.

Generally, the dielectric elastomer actuator often needs several kilovolts for effective actuation and deformation.[100] In order to address this challenge, Ji et al.[101] proposed a stacking strategy to develop dielectric elastomer actuators with a low operation voltage below 450 V (Figure 4c). Based on the low-voltage dielectric elastomer actuator, an untethered insect-sized soft robot was built and could run quickly with a speed of 30 mm s^{-1}. The soft robot could also carry a payload of 950 mg, five times its body weight. Considering that single-layer dielectric elastomer actuator often shows limited actuation force, integrating as many layers of actuators as possible in a unit volume will be an effective strategy to provide a powerful actuation. Thus, Ren et al.[102] developed a dielectric elastomer actuator based on the multiple-layer fabrication method (Figure 4d). The multiple-layer design is

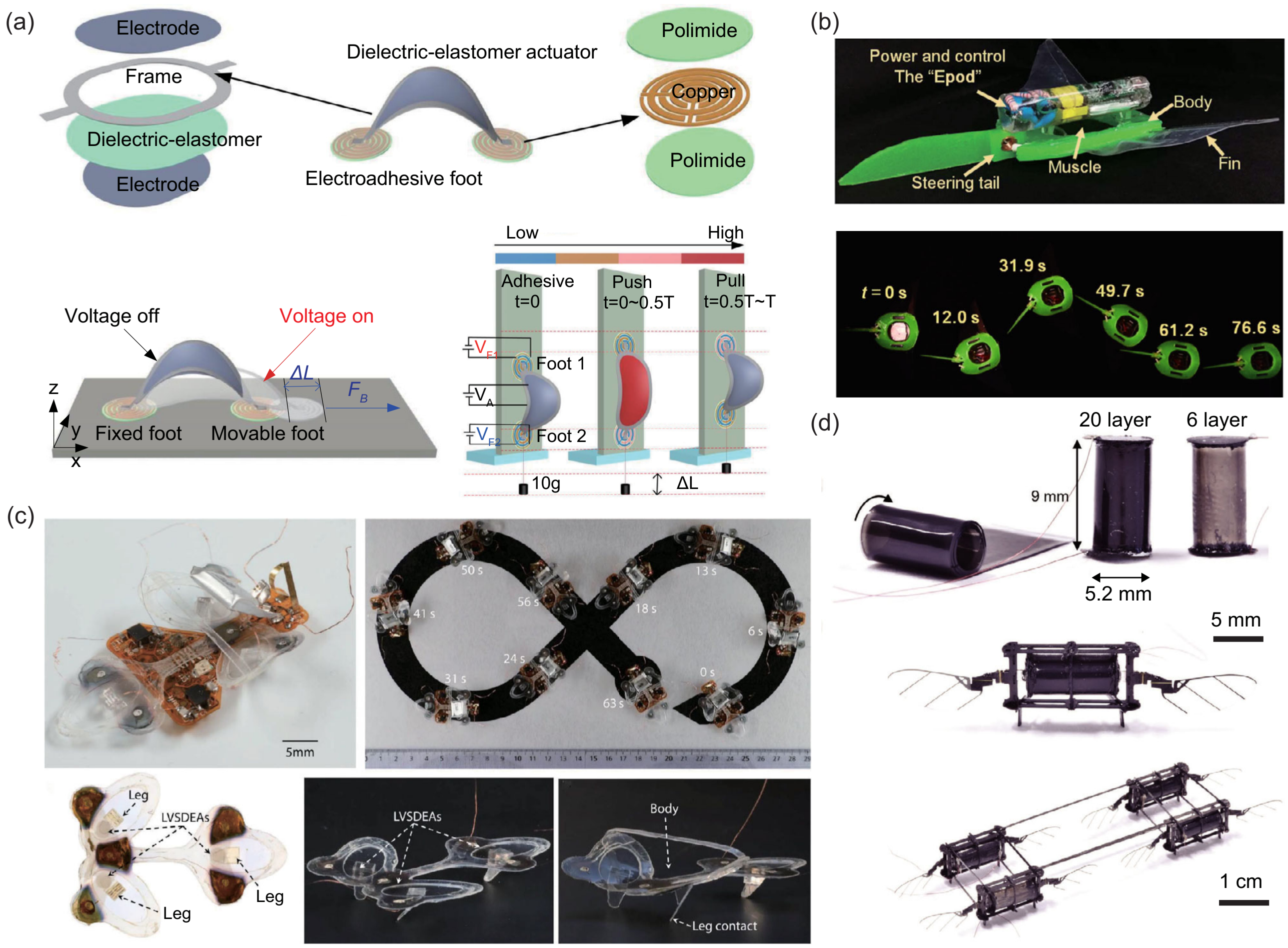

Figure 4. Dielectric elastomer-based soft actuators. a) Soft wall-climbing robots. Reproduced with permission.[94] Copyright 2018, AAAS. b) Fast-moving soft electronic fish. Reproduced with permission.[99] Copyright 2017, AAAS. c) Fast insect-sized soft robot based on dielectric elastomer. Reproduced with permission.[101] Copyright 2019, AAAS. d) Microaerial robot powered by dielectric elastomer actuators. Reproduced with permission.[102] Copyright 2022, Wiley.

powerful enough to act as the actuator in a microaerial-robot, which realized the lift-to-weight ratio of 3.7 at a low hovering voltage of 500 V. Among existing subgram aerial flight, this robot showed the longest and best flying performance with 2 million actuation cycles and 20 s of hovering time. In summary, dielectric elastomer actuator-based soft robots have realized the motion on land, in the sea, and sky.

2.4. Liquid Crystal Elastomer-Based Soft Actuators

LCE is a polymer network that is soft and anisotropic. The LCEs have a special thermal stimulation response property, which elaborates reversible deformation in macroscopic shape by disrupting and changing the local polymer network.[103,104] Significantly, this material will perform different deformation patterns according to various fabrication methods.[105] The LCE could contract, elongate, and twist depending on the preproducing process.[106] The deformation can be stimulated by light, heat, electronic stimuli, and magnetic with corresponding photothermal, electrothermal, and magnetothermal effect.[107–110] Removing the source of stimulation leads to the release of energy stored as mechanical energy. Combining this property with a proper design of the stimulation source, the actuator will be programmable and even acquire the ability of associative learning.[107,111,112] Several researches used these properties to fabricate artificial muscle,[112–114] soft robots,[115] and substance transporter.[116] LCE actuators are commonly controlled by light and electronic stimuli.[117] These methods are effective for most cases. However, the light-driven designs require the light source for stimulation, which is incompatible with the scenario that requires automated control in a complex working environment. Therefore, the electrical LCEs actuators will be a better choice in order to achieve convenient control in integrated systems.

Taking advantage of the deformation ability of the LCEs with good thermal response, thin flexible electrodes are a good choice to integrate with the LCEs to develop LCE actuators with electrothermal actuation. Schuhladen et al. reported an LCE iris that could unfold itself when heated by an integrated thin platinum electrode (**Figure 5**a).[118] In this iris-like actuator, a single heating electrode could not realize the independently regional control that often requires multiple heaters to cooperate with each other.

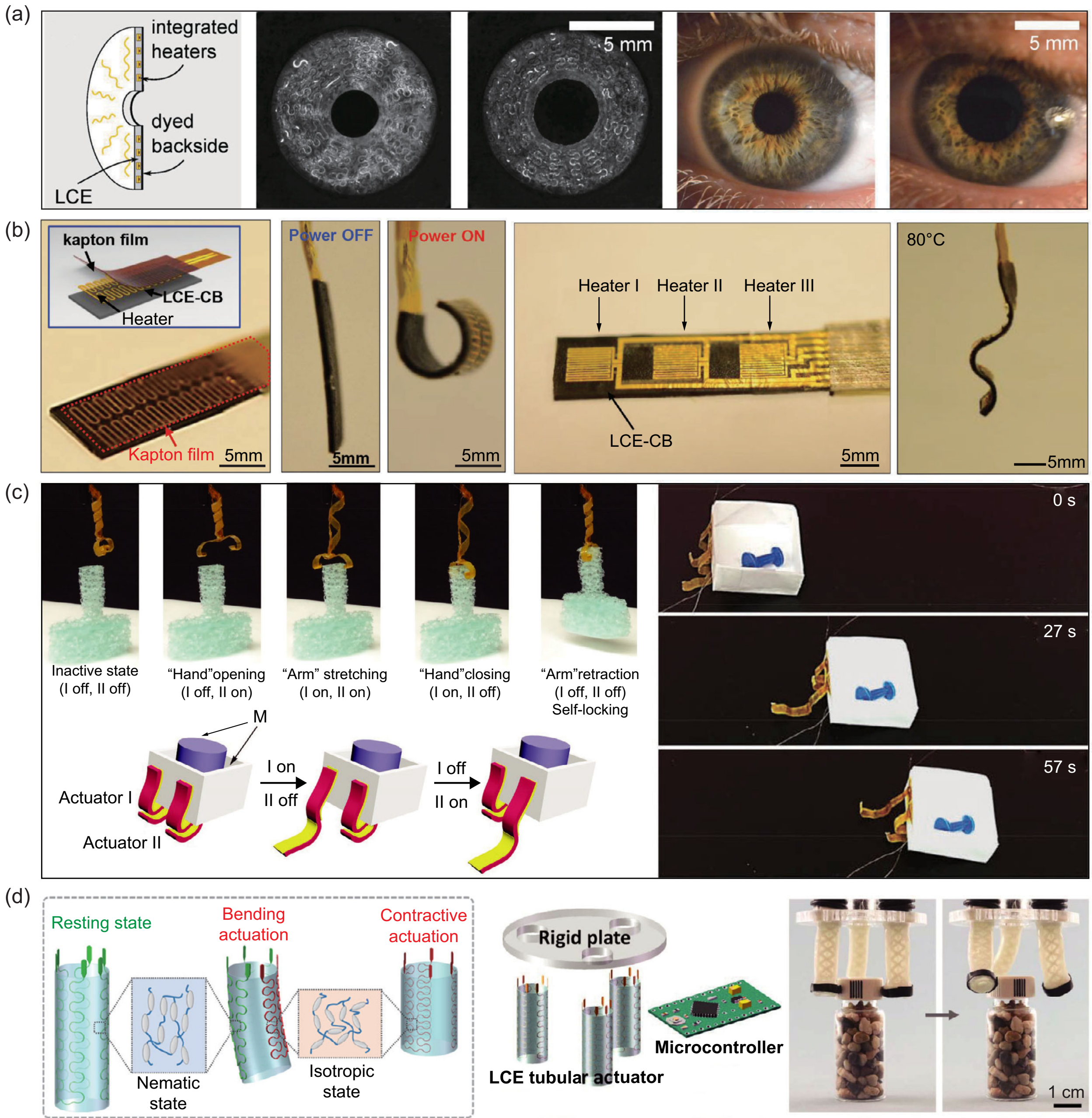

Figure 5. LCE-based electrical soft actuators. a) LCE iris with integrated thin platinum heaters. Reproduced with permission.[118] Copyright 2014, Wiley. b) Carbon black-doped LCE-based soft actuators with complex shape programming. Reproduced with permission.[119] Copyright 2018, Wiley. c) Liquid crystal polymer-based "Janus" soft actuators and robots with various types of biomimetic locomotion. Reproduced with permission.[120] Copyright 2019, Wiley. d) LCE-based soft tubular actuator with multimodal actuation. Reproduced with permission.[121] Copyright 2019, AAAS.

For example, Wang et al.[119] fabricated an inchworm mimicking 2D soft robot controlled by electrical stimulation that can bend in a designed direction. As shown in Figure 5b, the soft robots had a sandwich structure constructed with heater, carbon-black-doped LCEs, and Kapton film. When heated by the flexible electrode, the LCE layer in the actuator shrank and the bilayer actuator bent to the LCE layer side. When the electrical stimulation was removed, the stored mechanical energy was released, and the bilayer recovered to its initial status. With the specific arrangements of the heaters and stimulation patterns, the actuator could bend into programmable shapes. In this research, by changing the arrangement of facing and location of the Kapton film and the heater, the "S" deformation shape was realized. To fulfil more complex tasks, the higher freedom of mobility is acquired. Xiao et al.[120] introduced a programmable soft robot that could complete complex tasks of grabbing and transporting substance (Figure 5c). This soft actuator could be reprogrammed by changing the arrangement of the Kapton layer and the LCEs. With the preprocessing of the shape, the actuator with a 3D shape was acquired. While using the specific 3D shape, combining several actuators could complete more complex targets. For example, a self-locking gripper and a robot arm that could stretch and elongate in vertical direction was assembled together to realize a controllable human hand-like robot system. By integrating two actuators as the legs, a robot acting as a conveyor could push a container forward, which puts forward the possibility of fabricating the robot capable of fulfilling complex tasks. In fact, these thin 2D actuators can be made not only into spirals, but also into other shapes by simply bonding. He et al.[121] introduced a tubular actuator that could elaborate the bending and contraction individually in multiple directions. As shown in Figure 5d, a tubular LCE actuator was fabricated with three serpentine heaters. Comparing with other designs, the commonly used Kapton film is absent in this actuator. When specifically heating the actuator, the mixed activity of bending and contraction could be achieved. For example, three actuators were installed to a ridged plate and worked synergistically as a gripper, which was used to grab the vial and twist the cap. Advanced structural design and innovation can significantly improve the function of robots.

Based on the thermal responsive property of LCEs, more applications have been proposed. Wani et al.[122] proposed a flytrap-mimicking device that was self-regulated and compatible to recognize the object. Schuhladen et al.[118] introduced an iris-like aperture that is tuned by magnetic field. Deng et al.[116] utilized the planar-aligned LCE as the actuator to realize the pumping and coupling of the liquid. LCE exhibits excellent characteristics in the thermal response; however, the response time of LCE is relatively slow. Under electrical heating, LCEs need to take several seconds to fully transform into the desired deformation objective.[112] The slow response is a major disadvantage for electrical LCE actuators if rapid response is required in the application.

2.5. SMAs-Based Soft Actuators

SMAs are a special class of alloy materials that can memorize their initial shape and recover under certain conditions, that is, plastic deformation of SMAs caused by external stimuli, such as the most common deformation caused by stress, can be restored to the initial state after the temperature rises up to the critical temperature.[123,124] The ability to memorize and recover the initial shape is given by the temperature-induced reversible crystalline phase transformation of SMAs: the crystalline phase exists as martensitic crystal structures possessing low Young's modulus at low temperature, but when the temperature exceeds the transformation temperature, the martensite transforms into austenite which can exist stably at high temperature and possesses a higher Young's modulus.[125–127] Interestingly, such shape memory behavior induced by reversible crystalline phase transformation can convert heat into mechanical motion of SMAs, which is widely studied and employed to design and fabricate portable soft actuators.[93,126] SMAs possess excellent work density and considerable deformation range and are therefore considered a potential alternative for manufacturing actuators.[127] Not only that, the unique advantages of SMAs, such as lightweight and straightforward design, further broaden their application scope in aerospace,[128] soft robotics,[129] biomedical engineering,[130,131] etc.

SMA wires are often utilized in the fabrication of 2D soft actuators through simple structural design. Hwang et al.[132] reported a 2D soft actuator by applying prestrain to commercial SMA wires and placing them eccentrically in silicone elastomers (**Figure 6**a). When the Joule heat generated from the electric current causes SMA wires to exceed the critical temperature, the eccentrically placed SMA wires will generate a shrinkage force, which will cause the entire silicone elastomer to bend to the weaker side. Further, the assembly or splicing of similar 2D soft actuators based on SMA can realize more complex motion forms, such as seal-inspired amphibious locomotion and even 3D motion.[129] A similar structural design based on SMA wires can also prepare the opposite motion process. The morphology of the 2D soft actuator is transformed from the initial bending state to the straightening state when activated. As shown in Figure 6b, Huang et al.[133] fabricated 2D soft actuators with fast responsiveness, which have curved initial shapes, by applying unilateral prestrain, and combined it with mature electronic technology to achieve LEGO-like assembly of multiple 2D soft actuators in different forms for soft robotics with more complex motion. The high work density and stable reversible deformation ability of SMAs are often employed to fabricate lightweight actuators, and more lightweight robots with exciting applications can be realized together with mature microelectronic technology. Zhakypov et al.[134] developed an origami robot with multilocomotion capabilities using SMA springs as actuators by combining with microelectronics technology (Figure 6c), and such millirobot with insect-scale size weighs only about 10 g due to the lightweight design of various functional components, and it can achieve complex locomotion such as somersault jump in the air.

In addition to fundamental actuation in bionic robotics, SMA-based soft actuators are also studied and developed in wearable devices and biomedical engineering. Kim et al.[135] arranged SMA wires between two arched elastic beams to fabricate a lightweight actuator with larger driving force and actuation strain and applied it to the focal alignment of augmented reality (AR) glasses (Figure 6d). The driving method of the SMA-based actuators is simple, and their working process does not require the assistance of additional huge devices, which provides convenience for their medical assistance in vivo, especially the force stimulation of certain organs or tissues. Hassani et al.[130] utilized the combination of SMA spring and SMA wires as the actuator in the closed-loop system to stimulate bladder urination (Figure 6e), and the actuator can stimulate mouse bladder to urinate according the monitoring data by the capacitive sensor, which is hard to achieve by piezoelectric materials with small strain arrange and dielectric elastomers requiring high-voltage assistance.

In addition to above electrically driven actuators, electromechanical actuation principle is also often used to develop 2D soft actuators.[136–140] These kinds of actuators convert electrical energy into mechanical energy via electrochemical processes.[136,141–143] They were usually fabricated into a sheet shape that consists of two electrode layers and an electrolyte layer. The materials of the electromechanical actuators can be divided into three main types: metal-based, nanocarbon-based, and polymer-based, which are actuated based on different principles including changes in the lattice parameters, changes in valence states, chemical adsorption

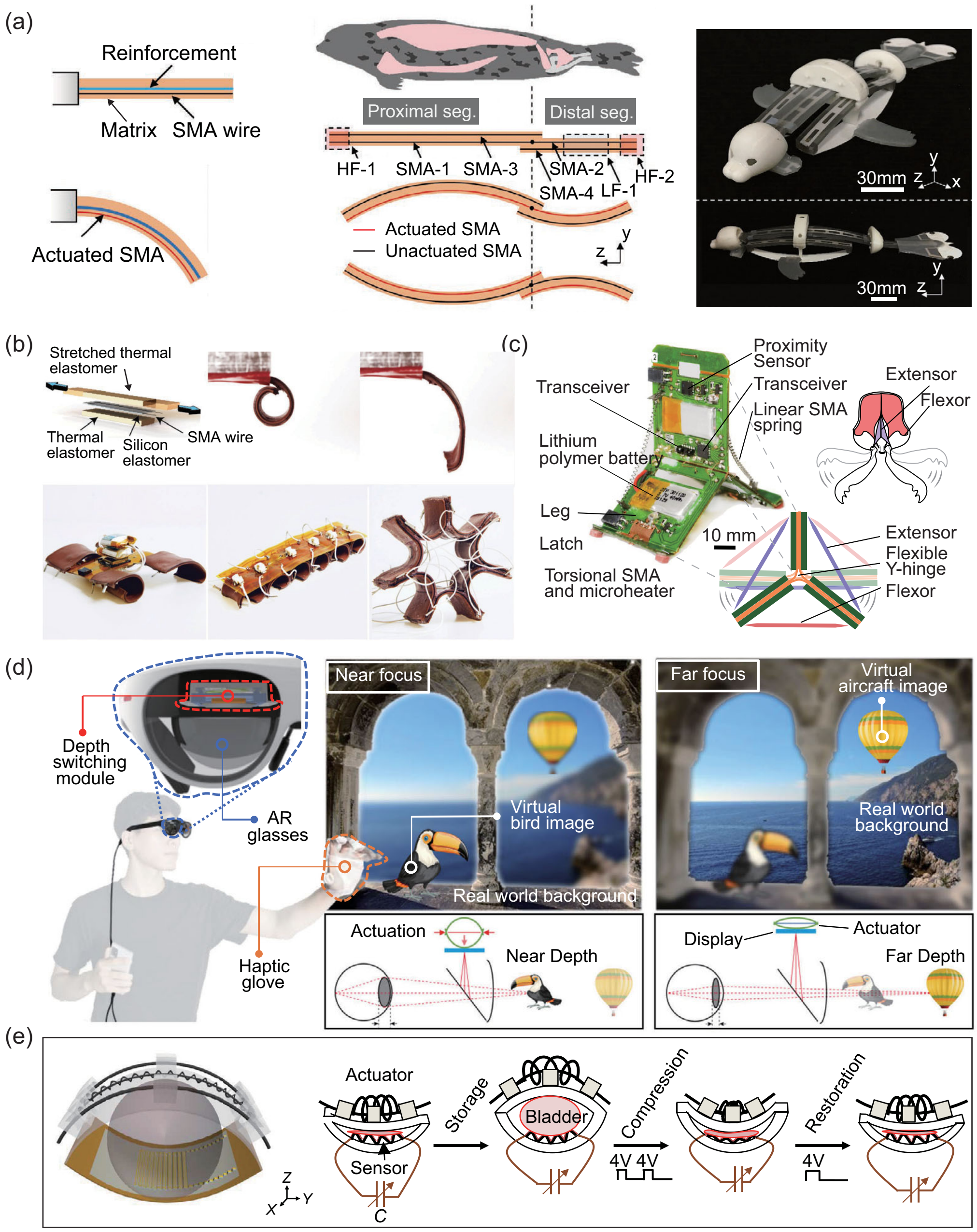

Figure 6. SMAs-based soft actuators. a) 2D soft actuators based on SMA wires and their application in seal-inspired locomotion. Reproduced with permission. Copyright 2022, Wiley.[132] b) 3D soft robot obtained by structural assembly of 2D soft actuators. Reproduced with permission.[133] Copyright 2019, Wiley. c) Millimeter robots with complex motion capabilities based on SMA springs. Reproduced with permission.[134] Copyright 2019, Springer Nature. d) SMA actuators with designed structures for focus alignment in AR glasses. Reproduced with permission.[135] Copyright 2022, Springer Nature. e) SMA actuators of closed-loop systems in vivo for mouse bladder stimulation. Reproduced with permission.[130] Copyright 2020, AAAS.

of ions, intercalation and delamination of ions, inhalation and detachment of ions, and inhalation and detachment of H_2O molecules.[144] When a voltage is applied on the electrode layers, these actuation mechanisms all lead to bending deformation. The electromechanical actuators show some significant advantages in low actuation voltage, high strain, and fast response, which are suitable for low-voltage actuator development and wearable actuation system integration.

3. 3D Soft Robots Based on 3D Electrical Actuation

We define soft robots or actuators actuated by multiple dimensional deformations as 3D soft robots or actuators, which often present 3D structural deformations. The 3D soft robot system can be constructed by piecing some 2D soft actuators together or by an integrated manufacturing method. In this section, we focus on integrated manufacturing methods, including 3D printing, origami, and 3D compressive buckling process.

3.1. 3D-Printed Electrical Soft Actuators

3D printing, also known as additive manufacturing, is a flexible, versatile technology for rapid prototyping of 3D objects and iteration of customized products.[145,146] The core idea of 3D printing technology is to convert digital 3D objects into the fabrication of multiple 2D planar patterns, and the superposition of these layers forms the final 3D entity.[147,148] Since no auxiliary masks or molds are required, 3D printing enables one-step product manufacturing compared to traditional multistep manufacturing (integrated manufacturing and then cutting or other subtractive methods to obtain the final product) and greatly reduces the loss of raw materials in the manufacturing process. Commonly commercialized 3D printing techniques can be mainly divided into two types: layer-by-layer fabrication based on photoinitiated surfaces and line-surface-volume fabrication based on extruded filaments, which have a wide range of research and applications in many fields, including tissue engineering,[149,150] flexible electronics,[151,152] and soft robotics.[153]

Soft actuators and soft robotics usually involve multimaterial coordination and soft material molding, and 3D printing technology is undoubtedly a powerful alternative to traditional manufacturing processes. Kotikian et al.[154] fabricated hinges connecting polymer sheets by extruding 3D-printed LCEs, which enabled untethered and flexible origami-like robots (**Figure 7**a). Interestingly, the geometric orientation and thickness of the filaments during the 3D printing process enable control over the form of motion, which is bottom-up structural programming. Benefiting from the versatility of extrusion 3D printing, in addition to LCEs, some electrically responsive gel materials can also be extruded into filament form to fabricate soft actuators with desired structures after simple rheological modification, which greatly broadens the design ideas of soft actuators with special structures. Wang et al.[155] used dibutyl adipate to modify the

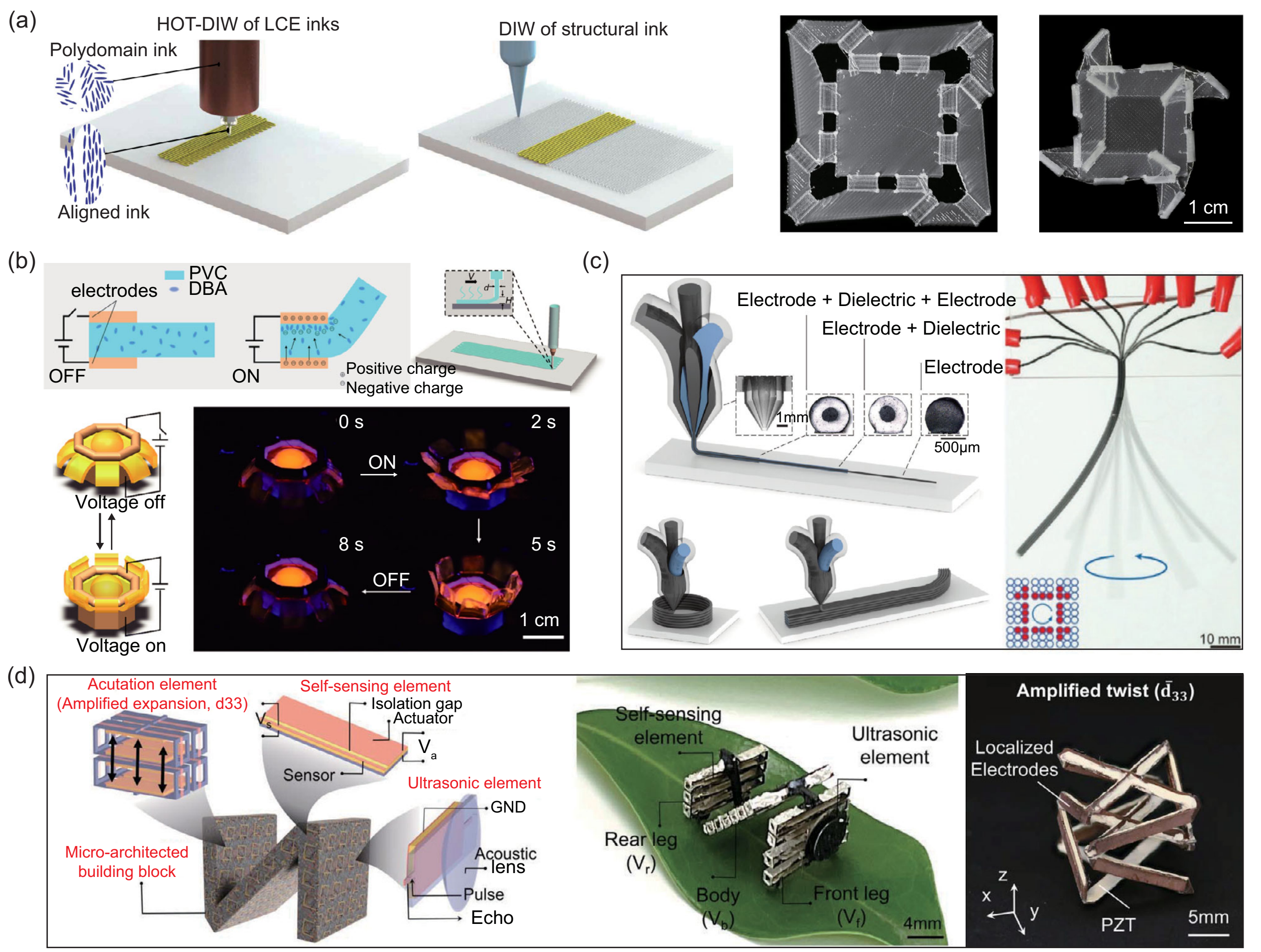

Figure 7. 3D-printed electrical soft actuators. a) 3D-printed LCE hinges as origami robot actuators. Reproduced with permission.[154] Copyright 2019, AAAS. b) 3D-printed PVC gel actuators for jellyfish-like robot with fast electroresponsive capability. Reproduced with permission.[155] Copyright 2021, ACS. c) Coaxially printed soft actuation fibers based on dielectric elastomers. Reproduced with permission.[156] Copyright 2021, Wiley. d) Photoinitiated 3D-printed microrobot integrated with multiple materials. Reproduced with permission.[158] Copyright 2022, AAAS.

rheological properties of PVC dissolved in tetrahydrofuran, enabling direct extrusion printing of mixed solution (Figure 7b). Based on this strategy, an electrically responsive jellyfish-inspired robot capable of reversibly opening and closing can be directly printed without the need for complex electrical structures.

3D printing technology can not only print simple filaments that can only work by combining into integral planes, but the flexible configurability of extrusion 3D printing, such as coaxial printing, provides more opportunities for manufacturing soft actuators with more diverse structures. Chortos et al.[156] fabricated electrically driven soft fibers with a three-layer coaxial structure (electrode–dielectric elastomer electrode) through a coaxial extrusion printing process (Figure 7c), which exhibits radial contraction and axial elongation behavior at the same time when applying a voltage. Further, these fibers can be stacked into different structures (vertical coils, bundles) by 3D printing technology to achieve the structural programming of various motion forms. Another common type of 3D printing technology is based on photoinitiated solid fabrication, which is often used in the manufacture of hydrogel actuators and materials such as resins, and the manufacturing process usually involves crosslinking reactions under the action of photoinitiators.[146,157] Cui et al.[158] used photoinitiated 3D printing technology to integrate piezoelectric materials, conductive components, and main structures to fabricate a microrobot with multidegree-of-freedom motion capabilities (Figure 7d), which is difficult to achieve using traditional manufacturing techniques. In general, there are various strategies to achieve 3D printing of soft actuators, which also provides opportunities for soft actuators with more complex structures and multimaterial components to satisfy the gradually upgraded application needs. What is even more attractive is that 3D printing technology has dramatically reduced the period and cost from digital design to prototyping of a single complex product, which significantly facilitates the rapid iteration and product design based on soft actuators.

3.2. 3D Origami Electrical Soft Robots

Origami is the craft of folding paper to make models of animals, people, and objects. In nature, the origami process is very common, such as the process of flowers opening during the day and closing at night in many plants, the folded morphology of insect wings.[159] In engineering, origami is the folding process with a structure created from a sequence of spatially organized folds.[160] These structural main frames can be made of thin paper or rigid structures that are folded along creases to create origami structures. A flat structure can be folded into a 3D structure by a specific design, which provides an opportunity to simplify and accelerate the design and fabrication of 3D soft robots that are called origami soft robots.[161,162] The origami manufacturing process is quick, efficient, and flexible to construct an integrated 3D robot without the need for complex and high-precision assembly.

Based on a variety of structural design, origami soft robots can be used in many engineering and biomedical fields. For soft manipulation, many soft origami robots actuated by an air pump performed as a soft gripper to grab objects[163–165] with intelligent sensing functions.[166,167] In the field of machinery manufacturing, origami was employed to build transformable car wheels that showed a high weight-to-payload ratio.[168] Further, inspired by the folded morphology of biological wings, origami is a very good tool to develop small aircrafts for flight movements with retractable wings.[169–171] Moreover, soft arms and grippers with origami structures could be integrated into an aircraft to assist the drone to perch on a tree branch[172] or deliver cargo.[173] In the biomedical field, magnetic materials could be used to develop soft 3D robots using origami technology.[174–176] The magnetically actuated small-scale origami crawler with in plane contraction is promising to be used for in vivo drug storage and release.[177] In addition, the origami robots were also utilized to monitoring physiological signals, such as blood pressure and electrocardiogram (ECG).[178] For example, a 3D origami smart insole was reported to monitor the foot pressure distribution for gait analysis of patients, and the 3D origami-structured electromyography (EMG) fingers could also be installed in the humanoid hand for EMG signals detection.[179]

In view of the multiple applications of origami robots and the advantages of electrical actuation in system integration, electrical 3D origami robots are attracting more attention. Zheng et al.[180] reported modularized origami soft actuators consisting of SMA wires, foldable paper-based heaters, and paper substrates with special origami structures. SMA wires are threaded into the paper as an actuation module. In this actuator, the entire origami device was actuated by the tensile deformation of a single heating electrode, which cannot show multidirectional control. In fact, many 3D origami robots tend to control the entire origami system by independently actuating each joint. In our previous work, we reported a programmable 3D soft robot based on the origami-inspired folding assembly of dielectric elastomers (**Figure 8**a).[181] Based on the design of the planar structure and multiple independently controlled soft actuators at different locations, the 3D soft robots with various shapes such as pyramids and cubes were constructed via programmable out-of-plane deformations. Moreover, the origami robot also showed easy switching between 2D and 3D structures, which allowed the 3D soft robots to be used as soft manipulators for grasping and precisely locking 3D objects. Furthermore, the electrical origami robot can also be actuated wirelessly. Boyvat et al. reported a battery-free wireless folding method for dynamic multijoint structures with addressable folding motions using only basic passive electronic components on the device.[182] As shown in Figure 8b, a robotic arm with three-coil SMA actuators (two for the arm and one to control the gripper) could turn left, right, and pitch by selective actuation of the two actuators at each side of two spherical six-bar origami patterns. Meanwhile, the gripper on the robotic arm could open by the actuation of the SMA connected to the gripper. In addition to these millimeter- and centimeter-scale structures, electrical origami can also be achieved at the micrometer scale. As demonstrated in Figure 8c,[183] Liu et al. reported micrometer-sized electrically programmable shape-memory actuators for low-power microrobotics. The actuators worked based on the electrochemical oxidation/reduction of a platinum surface to create a strain in the oxidized layer for bending deformation, which

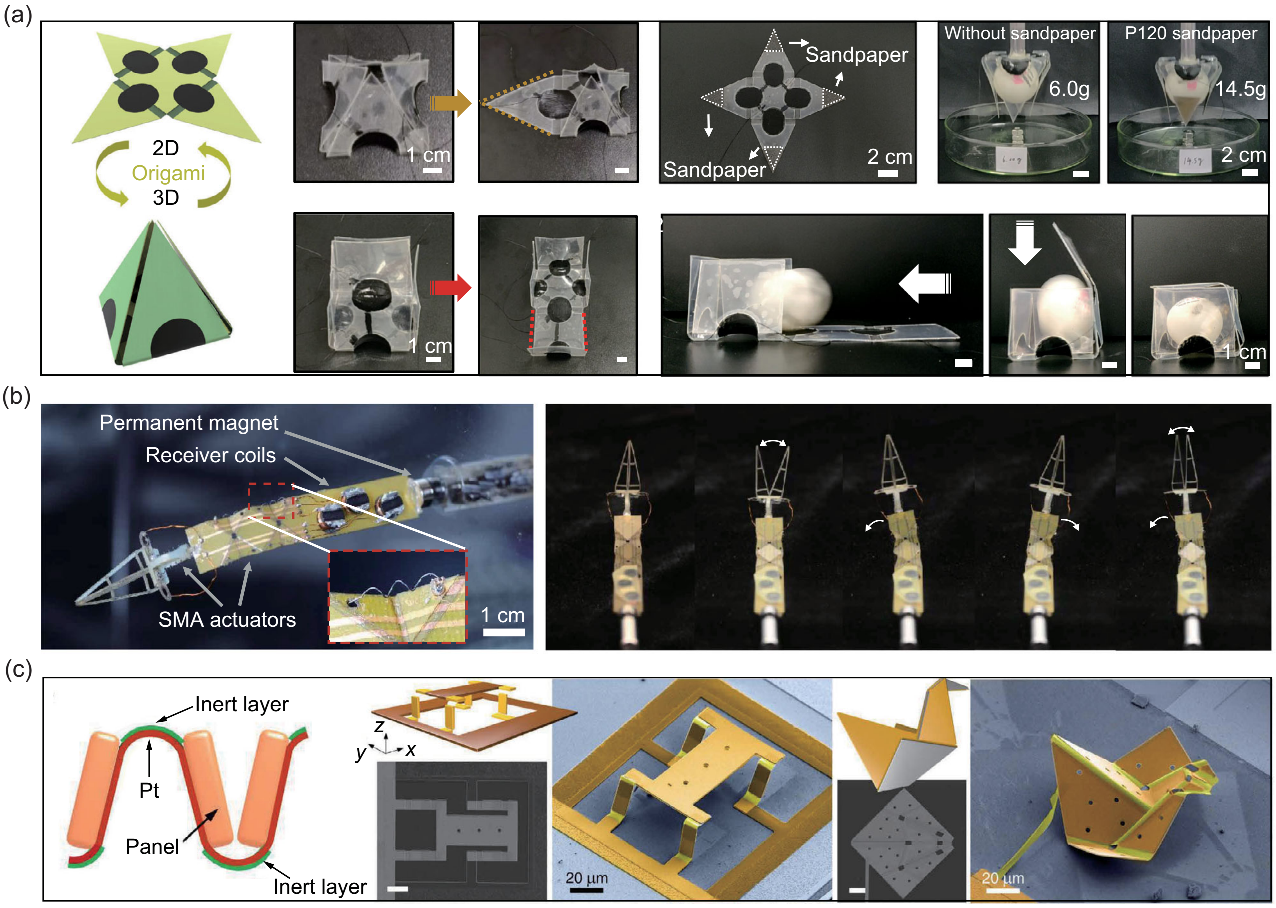

Figure 8. 3D origami electrical soft robots. a) 3D programmable soft robots based on the origami-inspired folding assembly of dielectric elastomers. Reproduced with permission.[181] Copyright 2022, Springer Nature. b) A microorigami robotic arm. Reproduced with permission.[182] Copyright 2017, AAAS. c) Programmable shape-memory actuators-enabled multistable micropositioners and microscale origami duck. Reproduced with permission.[183] Copyright 2021, AAAS.

provides a very efficient way to create a basic electrically reconfigurable origami-based 3D microscale robot.

3.3. 3D Soft Actuators Based on Buckled Structures

In addition to 3D printing and origami self-assembly methods, as a new 3D processing method, 3D compressive bulking process is also an excellent choice for developing 3D soft actuators and robotic systems. 3D compressive bulking that deterministically transfers various 2D planar precursors into 3D architectures based on a series of mechanics designs has greatly broadened its application in the fields of cell/tissue engineering, biointegrated electronics, soft actuators/robotics, and many others.[184–186] Recent works have demonstrated its advantages of 1) a variety of materials availability (conductors, semiconductors, insulators, and their heterogeneous combinations); 2) a wide range of size scales, ranging from nanometers to centimeters; and 3) mature processing methods of micro-/nanofabrication in semiconductor industry (dry etching, wet etching, and many others) and thus, making it a promising candidate for the development of soft actuators/robotics.[187,188] This part reviews the processing methods, integration strategies, and system-level application of the 3D buckled architectures that can be potentially adopted in actuators/robotics for biomedical applications.

3.3.1. 3D Compressive Buckling Process

The fabrication process via 3D compressive buckling normally begins with the patterning of a 2D precursor on an underlying sacrificial layer to enable the subsequent transfer printing process (**Figure 9**a).[189–192] Patterning of the 2D precursor into desired patterns can be achieved by facilitating the sophisticated technologies in micro-/nanofabrication,[32,193–196] including dry etching, wet etching, and laser cutting etc. Removing the sacrificial layer enables transfer printing the patterned precursor to a freestanding stamp (water-soluble tape or PDMS stamp). Then, the freestanding 3D precursor is patterned with surface chemistries on a set of selected regions to define the bonding sites before being laminated on a prestretched elastomer substrate. Releasing the prestretched substrate introduces compressive stresses on the precursor between the defined bonding sites, thereby leading to delamination of the 2D precursor on the unbonded area. Consequently, 3D architectures are formed based on a coordinated set of rolling and buckling deformations.

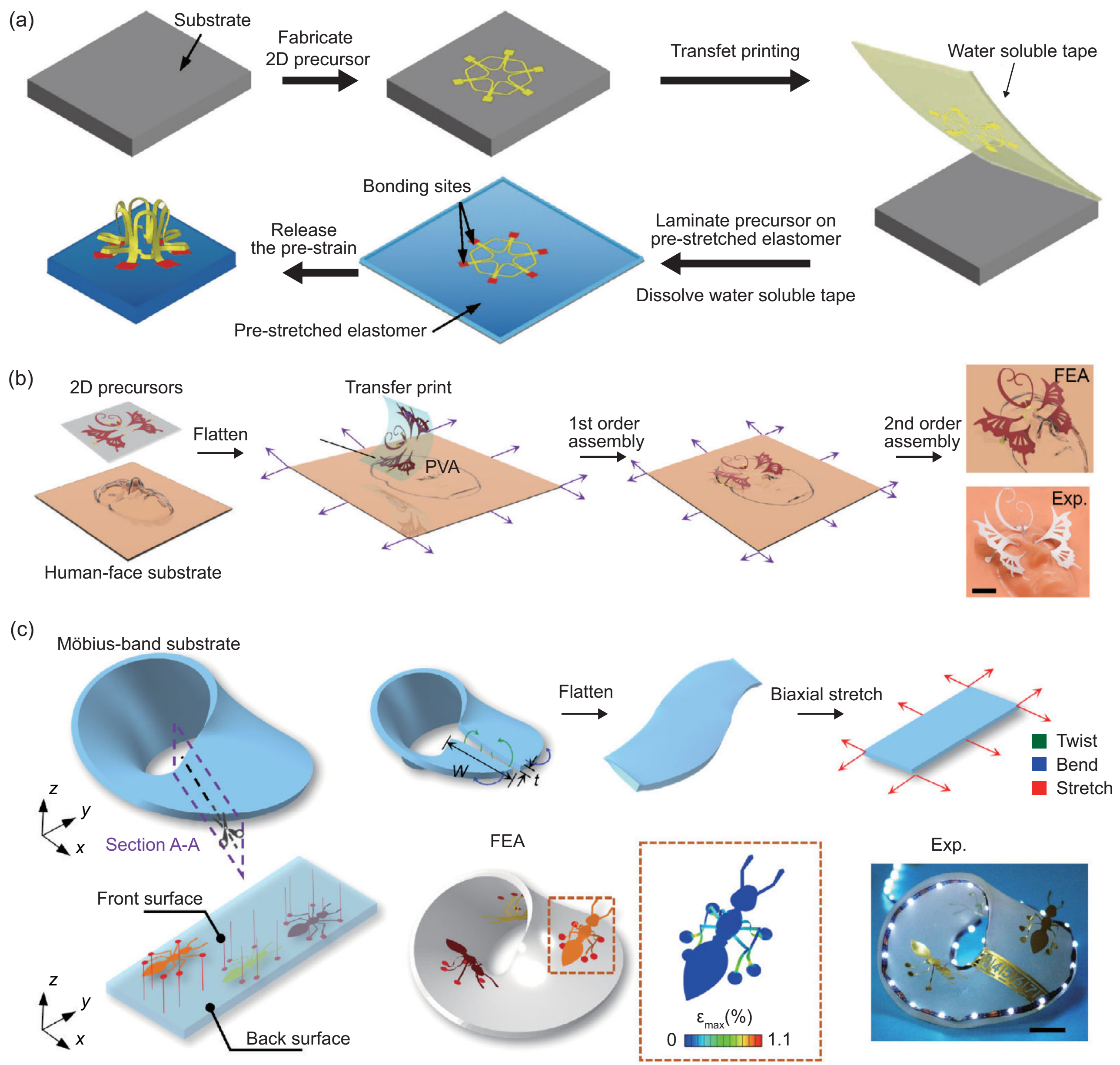

Figure 9. 3D compressive buckling process. a) Schematic illustration of 3D compressive buckling 2D precursor on planar substrate. Reproduced with permission.[189] Copyright 2018, Wiley. b) Schematic illustration of 2 order assembly process. Reproduced with permission.[204] Copyright 2022, AAAS. c) Processing method that integrates spider 2D precursor on mobius curved substrate. Reproduced with permission.[204] Copyright 2022, AAAS.

There are three key processing parameters, structural design of 2D precursors, selection of bonding sites, and magnitude and orientation of the prestretched elastomer substrate.[187,188,197,198] Theoretical calculation and simulation provide quantitative instruction for the design process and consequently provide a quantitative evaluation of the experiments.[193,199,200] Great freedom in structural design and flexibility in tuning the magnitude and orientation of prestrain in elastomer substrate facilitate the design and fabrication of complex 3D geometries.[201–203] However, it is hard to integrate the bulk 3D structures with 3D surface or complex 3D architectures that are usually needed in 3D actuators designed for complex application scenarios. To solve the aforementioned problem, Xue et al.[204] proposed a two-order assembly process to integrate the bulk 3D structures with 3D architectures. The first assembly is introduced to convert the 3D architectures into the 2D planar substrate, followed by the second-order assembly to bulky the 2D precursors into 3D format (Figure 9b). With this design concept and assembly strategies, they presented the capability of integrating the 2D precursor with almost arbitrary 3D curved substrates, including not only some regular surfaces, such as hemisphere, cylinder, but also some complex and biomimetic surfaces, such as the human face (Figure 9b) and Mobius band (Figure 9c). Meanwhile, quantitative theoretical analysis based on finite-element analyses can accurately capture the deformation behaviors of 2D precursor and 3D substrates, thus providing an efficient instruction for the whole process.

3.3.2. Freestanding Buckled Structures for Soft Robots

Great design freedom and almost arbitrary complex 3D architectures of 3D compressive bulking have greatly broadened the application of 3D bulk structures, ranging from electronics to robotics.[184,205–209] However, the fixed bonding sites between the 2D precursors and elastomer substrates have greatly limited the design and application of 3D bulk structures in the field of soft actuators/robotics.[210] Consequently, a wide set of promising actuating materials, structures design, and integration strategies have been developed for the integration of 3D bulk structures and functional actuating materials to convert those architectures into freestanding or shape-controllable formats. The promising actuating materials, including SMAs[211], shape memory polymers (SMPs),[212] liquid crystals,[213] and polymer composites,[214] not only provide stimulus for actuators under different external stimulations, such as electricity, heat, light, and/or multistimulus, but also maintain the buckled structures after the bonding sites between 2D precursors and substrates are removed.

SMA that generates mechanical motion via reversible crystalline phase transformation between martensite and austenite has been proved a promising candidate for the driving module of freestanding 3D buckled architectures for the fabrication of microrobots.[211] With the system design of the planar PI skeleton and the selection of SiO_2 bonding sites, a crab-like microrobot was fabricated (**Figure 10**a). SMA is then selectively deposited on the joints to provide restoring force enabling various motion modalities after the removal of elastomer substrate. Under the driving of a controllable laser beam, reversible crystalline phase transformation occurs in the SMA due to the accumulating of Joule heating, generating a high-speed local motion of the microrobot, up to 0.44 body length s^{-1}. Similarly, Park et al.[215] integrated a class of 2D precursors with SMP for the fabrication of an aquatic robot, in which the mechanical motion generated by the crystalline phase transformation was utilized to release the stainless steel cargo and change the swimming mode of the aquatic robot (Figure 10b). After the release of the cargo, the robot moves in a circuit trajectory due to the multidirectional generated oxygen. In addition to SMP and SMA, LCEs that generates reversible shape change due to the coupling between the alignment and reconfiguration of liquid crystal molecules have also been involved in the fabrication of freestanding 3D buckled actuators. A 3D gripper was fabricated with LCE film by Li et al.[213] for the illustration of application potential of 3D buckled structures in robots and artificial muscles. Objects with regular shape (polyurethane ball) and irregular shape (soft 3D fish model) were successfully grabbed and released by morphing its 2D and 3D configurations (Figure 10c).

Aforementioned designs and structures demonstrated the possibility for the application of freestanding 3D buckled architectures in soft actuators/robotics by combination with activating materials. However, the external triggers for shape reconfiguration are either laser or temperature change, both of which make it difficult for simple and precise control of the actuators. Consequently, Ling et al.[216] presented a trilayer structure composed of polyimide (PI), polydimethylsiloxane (PDMS), and laser-induced graphene (LIG) that are capable of realizing reversible global folding and bending of a predesigned actuator under the stimulation of Joule heating generated by LIG. Figure 10d presents the experimental results and quantitative simulations of various 3D architectures enabled by global bending, flower-like structures, and local bending, ring mountain-like and ridge-like structures. Selectively bonding of the trilayer soft actuator with a flexible substrate on predefined bonding sites endows the systems with the capability of controllable 3D geometries under the trigger of electrothermal actuation (Figure 10e)

3.3.3. 3D Buckled Electrical Soft Actuators

With a class of structural designs, activating materials development, and system integration strategies, various 3D buckled actuators, either bonding with substrates or in freestanding forms, have been developed. Integration at the process and system levels has greatly enabled a significant increase in the applicability of 3D buckled actuators/microrobots in the field of microelectronics and bioelectronics.[217,218] Kim et al.[219] developed an electronic microflier based on the 3D buckled SMP precursor. With the theoretical simulations and geometrical optimizations, 3D fliers with controllable rotational kinematics and terminal velocities were developed for the measurement of local pH and dust pollution via system integration with pH indicator and electronic components (**Figure 11**a). Besides, thin-film piezoelectric materials, lead zirconate titanate (PZT), was integrated with table-shaped and fly-shaped 3D buckled structures for the measurement of liquid viscosity and density (Figure 11b).[220] High-frequency vibration of the buckled structures can be generated under the activation of the active PZT module with a high-frequency voltage as input. Meanwhile, the system response under high-frequency vibration is recorded by the PZT sensing module. The properties of surrounding liquid, viscosity, and density can be calculated by analyzing the voltage outputs of the sensing module. This 3D integrated system provides the feasibility of achieving an active, biointegrated system for the application of cell and tissue engineering.

Overall, these electrically driven soft actuators have been summarized and described in detail from a dimensional perspective. To present a clear and comprehensive sight on the different types of soft actuators, we draw a table to summarize the actuators' dimensions, actuation voltage, temperature, and applications (**Table 1**). These parameters and characteristics can provide important guidance for the development of soft actuators and the selection of actuation methods toward different practical application scenarios.

4. Conclusion and Perspective

Electrical soft actuators have inherent advantages in system integration and precise control, and therefore they will be major equipment in the future robotic system. In this review, we summarized various types of electrical soft actuators that function across dimensional scales from 2D to 3D, which played an important role in building both 2D and 3D robots. Based on

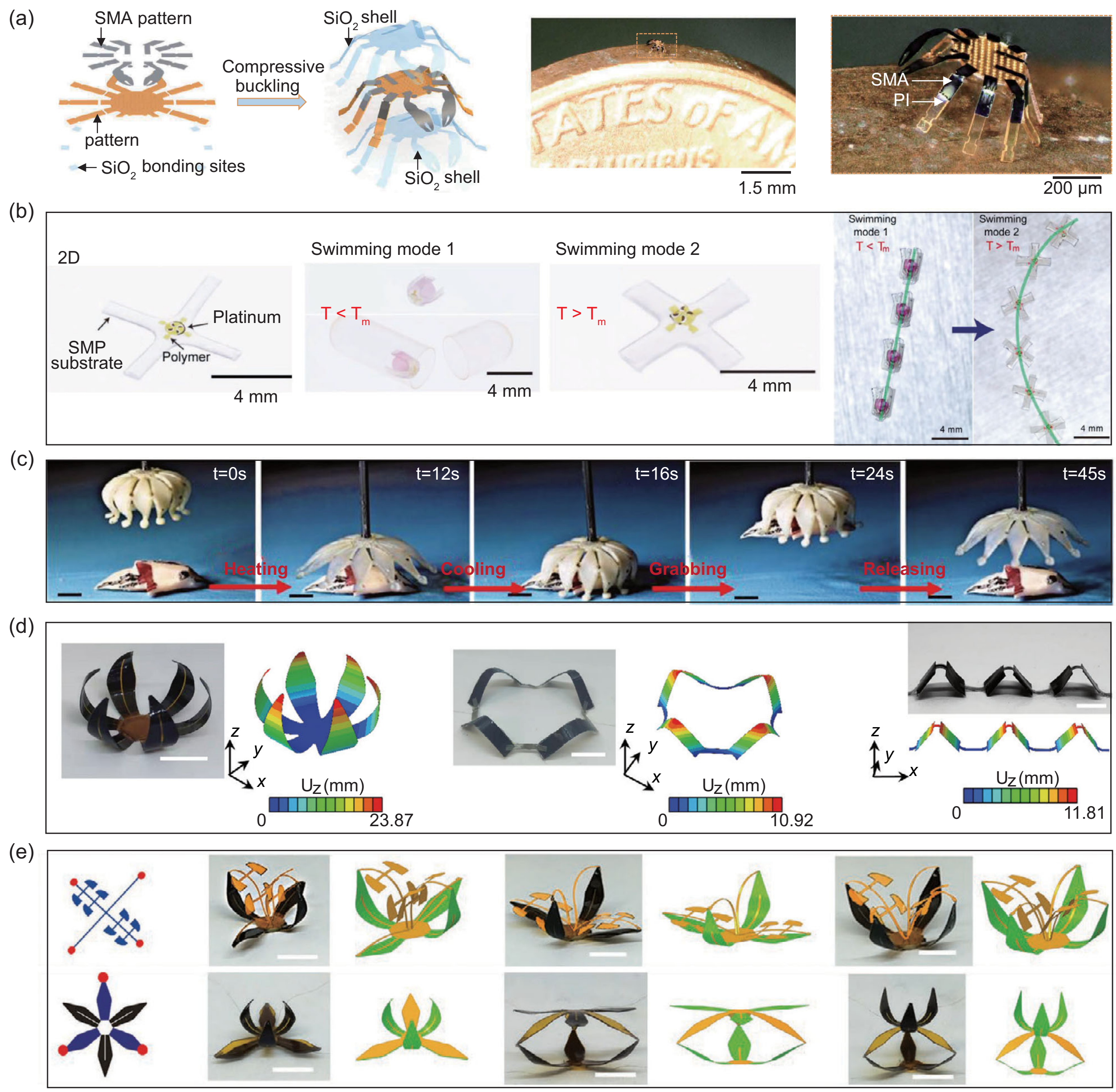

Figure 10. Freestanding buckled structures for soft robots. a) Components and optical image of a submillimeter robot. Reproduced with permission.[211] Copyright 2022, AAAS. b) Two types of 3D geometries and swimming modes of the SMP-based soft actuator. Reproduced with permission.[215] Copyright 2019, Wiley. c) Optical images and FEA simulations of liquid crystal selective bonded with substrate. Reproduced with permission.[213] Copyright 2021, Wiley. d) Structural designs and quantitative FEA simulations of the trilayer soft actuators. Reproduced with permission.[216] Copyright 2020, Wiley. e) Experimental results and FEA simulations of the controllable actuators selectively bonded with soft substrates to realize different 3D geometries. Reproduced with permission.[216] Copyright 2020, Wiley.

material design and structural design, the capabilities of electrical soft actuators can be greatly improved to enable them to perform well in robotic motion, engineering operations, and biomedical applications. Based on our introduction, we aim to assist researchers choose appropriate materials, structures, and fabrication method to build their desired 2D or 3D robot systems. Finally, we speculate that the future development prospects of electrical soft actuators or robots may focus on the following three aspects. First, the electrical soft actuator will be gradually used to replace the hard parts of the humanoid robot in order to realize the humanization of the robot in the material aspect. Second, on the basis of humanoid robot or manipulator, the closed-loop intelligent sensing and feedback in robotic control would be promoted to realize the humanization of the robot in the function aspect. Third, based on the wireless and digital advantages of electrical systems, biomedical soft robot systems

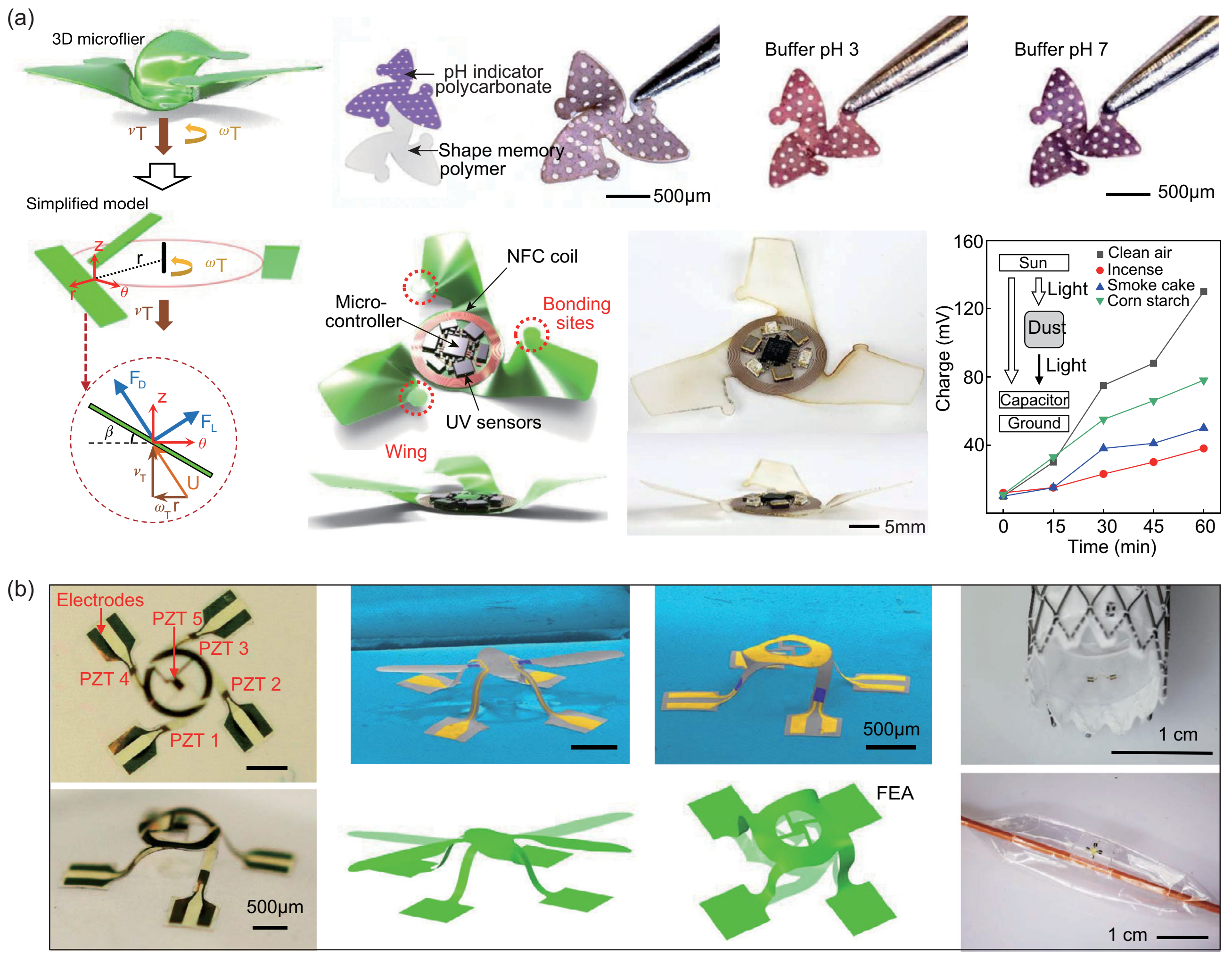

Figure 11. System integration and application of 3D buckled electrical soft actuators and robots. a) Structural design based on aerodynamics of the free-standing SMP-based 3D microfiler and its functional integration with pH indicator and UV sensor. Reproduced with permission.[219] Copyright 2021, Springer Nature. b) System integration of the table-shaped 3D buckled architecture and thin-film PZT serving as activation module and sensing module for the measurement of liquid properties. Reproduced with permission.[220] Copyright 2018, AAAS.

Table 1. Summary of the electrical driven soft actuators in dimension, actuation voltage, temperature, and applications.

Type of electrical driven soft actuators	Dimension		Voltage [V]	Temperature [°C]	Applications	References
	Actuation	Structure				
Thermal expansion-based actuator	2D	2D/3D	10–200	62–140	Artificial chameleon tongue, artificial vine, hand-shaped actuator	[68,69]
Piezoelectric actuator	2D	2D/3D	100–500	≈30	Artificial insect-scale fast robots, resonant millirobot, microscale aerial vehicle	[85–88]
Dielectric elastomer-based actuator	2D	2D/3D	450–10 k	≈30	Wall-climbing robot, swimming fish, untethered robotic insect, microaerial robot	[94,99,101,102]
LCE-based actuator	2D	2D/3D	3–50	78–120	Iris-like tunable aperture, Janus soft robot, gripper, walker, inchworm inspired soft robot, tubular actuator	[118–121]
SMAs-based actuator	2D	2D/3D	1–10	30–60	Soft amphibious robot, trap-jaw-ant-inspired tribot, soft rolling robot, AR glasses, bladder	[130,132–135]
3D-printed actuator	3D	3D	400–8 k	30–140	Self-propelling rollbot, jellyfish actuator, Janus coil actuator, piezoelectric metamaterial	[154–156,158]
3D origami actuator	3D	3D	1–5.5 k	/	Gripper, robotic arm, micropositioner	[181–183]
Buckled soft actuator	3D	3D	1–20	30–150	Swimmer, microflier, sensor	[215,216,219,220]

will be gradually studied to realize in vivo medical sensing and surgical treatment.

Compared with other input types of actuators, electric-driven soft actuators are easier to achieve programmable and precise motion control because the input source (electricity) is easy to manipulate through mature electronic devices. In the future, we can develop the desired robot system from the perspective of dimension and material designs according to the actual applications. As detailed in the previous content, the structural design of 2D actuators is simple and easy-processing, and the 2D actuators can be fully qualified for simple grasping and crawling movements in narrow spaces. In comparison, the 3D soft actuators can achieve more complex spatial multi-degree-of-freedom motion to meet more practical application requirements. Moreover, in recent years, the buckled 3D structure has been used as a novel design method for the manufacture of soft 3D actuators, which provides opportunities for precise manipulation of more complex spatial motion forms and in vivo sensing. From the perspective of material selection for the soft actuators, it should also be oriented to application scenarios and specific tasks. For example, to construct an in vivo or in vitro contraction brake device for assisting organ contraction, SMAs-based actuators are a preferred choice due to their large deformation and acceptable working temperature ranges. Although LCEs-based actuators and dielectric elastomers actuators can also exhibit powerful large deformations, their respective high-temperature and high-voltage requirement limit their biomedical applications (Table 1). However, in order to construct a fast-moving biomimetic robot, the dielectric elastomer turns out to be a suitable choice due to its relatively higher vibration mode than that of the SMAs-based actuators. Similarly, the higher frequency resonance exhibited by piezoelectric actuators is suitable for constructing such fast robots even though the deformation of piezoelectric actuators is small. Therefore, the characteristics and functions of each actuator presented in this review can establish a very informative guide for the construction of future robots.

At present, scientists have achieved a lot of research results in the flexible operation and controllable movement of electrical driven actuators and robots, but the research on the wirelessly electrical actuation is still relatively weak and challenging. The battery is a commonly used power supply device, but the volume and mass of the battery are more rigid and bulky than the flexible material of the soft robot, which will limit the mobility of the whole robot. Fortunately, radio frequency[182] and photovoltaic[88] power supply methods have also been studied and innovatively used in robot drives, which will be a good research trend. In addition, the functionalization of soft robots needs to be greatly expanded, not just limited to the robot's motion. In the future, soft actuators or robotic systems are required to have more functions in sensing, feedback, closed-loop control, healthcare and medical operations, etc.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

3D compressive buckling, 3D robots, electrical soft actuators, origami robots, soft robots

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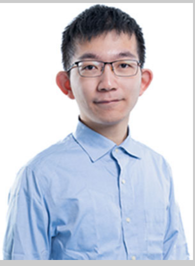

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