actuators

Review

A Review of Soft Actuator Motion: Actuation, Design, Manufacturing and Applications

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Abstract: Compared with traditional rigid robots, soft robots have high flexibility, low stiffness, and adaptability to unstructured environments, and as such have great application potential in scenarios such as fragile object grasping and human machine interaction. Similar to biological muscles, the soft actuator is one of the most important parts in soft robots, and can be activated by fluid, thermal, electricity, magnet, light, humidity, and chemical reaction. In this paper, existing principles and methods for actuation are reviewed. We summarize the preprogrammed and reprogrammed structures under different stimuli to achieve motions such as bending, linear, torsional, spiral. and composite motions, which could provide a guideline for new soft actuator designs. In addition, predominant manufacturing methods and application fields are introduced, and the challenges and future directions of soft actuators are discussed.

Keywords: soft actuator; actuation; design; manufacturing; applications

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1. Introduction

Traditional rigid robots are assembled from parts and structures with certain hardness and stiffness which are endowed with large load capacity and precise locomotion. However, it is difficult for these robots to conduct tasks in unstructured environments due to their high stiffness. Soft robots, show great advantages in flexibility, compliance, and adaptivity thanks to their soft materials and structures. They are widely adopted for grasping irregular objects [1–3] and minimally invasive surgery [4–6], which could broaden the working field of robots.

Soft actuators are crucial components of soft robots, and are fabricated by soft materials such as dielectric elastomers (DEs), electroactive polymers (EAPs), shape memory alloys/polymers (SMAs/SMPs), electroactive ceramics, thermoplastic polyurethane elastomers (TPUs), and hydrogels [7]. Soft actuators can be actuated by various stimuli, including fluid, thermal, electric, magnetic, light, humidity, chemical actuation, etc. Different actuation methods possess specific advantages. For instance, fluid actuation has the advantages of high energy efficiency, simple structure, flexibility and low cost [8–13]. Thermal actuation can avoid the need for bulky pumps and valve control systems to achieve wireless actuation [14–18]. Electric actuation has shown significant advantages in terms of fast response, non-loading stimulation manner, and easy integration [19–23]. Magnetic actuation can realize remote actuation for wireless soft actuators [24–27]. Light actuation has the advantages of remote directional and contactless actuation [28–30]. Humidity actuation can be realized by changing the humidity gradient of the environment [31–34]. Chemical actuation can be actuated by internal chemical reactions rather than external environmental stimuli [35]. Acoustic actuation is another potential actuation, which could transfer energy through sound waves to achieve locomotion [36–38].

Based on these actuation methods, specific motions are preprogrammed into the structures of actuators, which provide inexpensive and convenient methods for desired motions.

To achieve inchworm multimodal locomotion, Gu et al. presented a soft actuator that could complete a variety of locomotions, such as crawling, climbing, and transitioning between horizontal and vertical planes through the preprogrammed motion of the actuator [39]. To achieve object grasping purpose, Yoshida et al. proposed an internal exoskeleton gripper with variable stiffness pneumatic bending actuators based on low-melting-point-alloys, which was able to conduct a bending motion at different points and keep its bending shape without power input [40]. However, actuators with preprogrammed structures cannot achieve multiple motions by a single customized actuator. According to the preprogrammed structure, the constraints are embedded into the structure of the actuator, which cannot be changed to achieve specific motions. The reprogrammed structure of a soft actuator can adjust the structure constraints dynamically to achieve different deformations. Yoshida et al. presented an actuator in [41] which was able to achieve different motions (e.g., torsional and linear) by changing the fiber alignment. Yang et al. proposed a novel reprogrammable soft actuator which achieves spiral motion by tension jamming; the proposed jamming technology enables adaptive ability in the emerging actuator to deal with unknown environments [42]. Moreover, Cui et al. presented a soft microrobot which can be controlled to realize a specific shape transformation by programming magnetic configurations [43].

The presented literature provides a critical overview of the developments in soft actuators, including the actuation methods, preprogrammed structure design, and existing manufacturing types and applications, as shown in Figure 1. This article demonstrates the relations between actuation methods, preprogrammed structure design, and corresponding motions, which could provide a guideline for actuator design. At the end of this review, the continuing challenges and future directions of soft actuators are discussed.

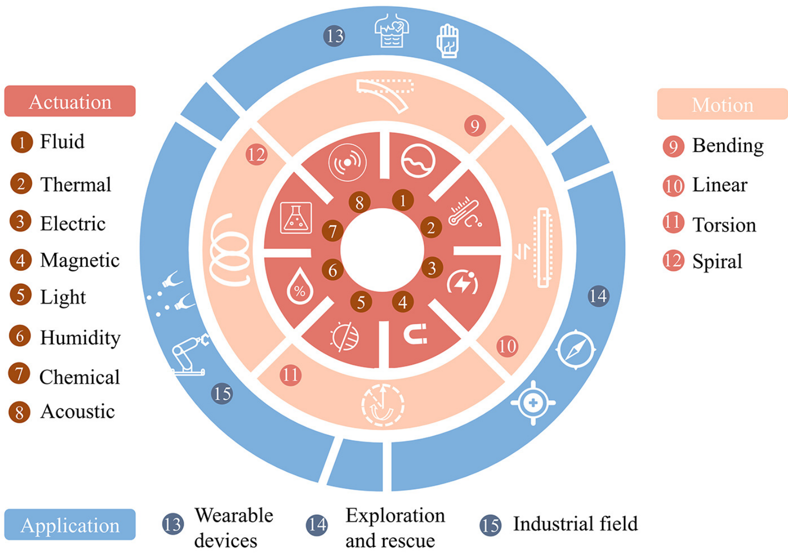

Figure 1. Actuation methods, motions, and applications of soft actuators.

2. Actuation

2.1. Fluid Actuation

Fluid actuation is one of the most common actuation methods for soft actuators, with high energy efficiency, large output force, a simple mechanism, and low cost. The medium of the actuation is divided into a compressible gas and incompressible liquid, which can be used to change the pressure of the sealed space made by flexible inflatable materials [44–47]. With changing volume in the confined space, expansion or contraction can be achieved. Moreover, the stiffness of flexible materials is the most important factor for this kind of actuation, as expansion or contraction always occurs first where the stiffness is minimal;

many motions can be achieved in this way. However, this actuation method is rarely used in wireless actuation, as it is usually accompanied by heavy auxiliary equipment.

2.2. Thermal Actuation

Thermal actuation is frequently used on intelligent materials which experience performance changes under application of thermal energy [48–50]. These materials can be divided into two different types: those in which the crystal structure of the material changes directly in the solid state, such as SMAs, and those in which the stiffness of the material is varied, such as SMPs.

Currently, SMAs are most widely used due to their high recovery stress. The crystal structure variation of nickel titanium (Ni-Ti) SMA is shown in Figure 2a. Specifically, the SMA can change modulus when it varies from austenite to martensite, which shrinks or expands from its initial shape with temperature variation [51–53].

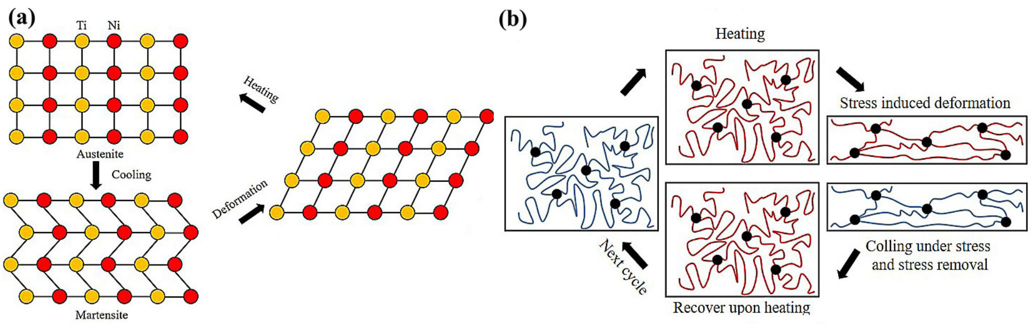

Figure 2. (**a**) The crystal structure variation of nickel titanium (Ni-Ti) SMA. (**b**) Schematic diagram of SMP deformation.

In addition, the stiffness ratio of SMPs can be as high as several hundred due to the change in the SMP molecular chain segments, as shown in Figure 2b. Specifically, the molecular chain segments transform from high stiffness to low stiffness when experiencing the transition temperature. The transition characteristics of SMPs provide an opportunity for realizing obvious deformations under the action of external force [54–58]. Wireless actuation can be achieved by tuning the temperature around the actuator. However, a significant drawback of this method of actuation is poor real-time ability and small output force.

2.3. Electric Actuation

Electric actuation has two main forms with respect to realizing functions. One is to change the stiffness of intelligent materials, such as electro-rheological fluids (ERF). The other is to make intelligent materials such as DE, ionic polymer–metal composites (IPMC), and EAPs deform directly.

The viscosity of ERF changes under the action of an electric field, which affects its stiffness [59,60]. Figure 3a shows the variation of ERF microstructure under electric actuation. ERF consists of dielectric particles and an insulating liquid, such as a Newtonian fluid. The randomly distributed dielectric particles are arranged in chains along the direction of the electric field. In this process, ERF changes from a high-viscosity gel state to a low-viscosity liquid state with stiffness variation.

Compared to ERF, DE can produce motion immediately under the action of direct current [61,62]. DE is squeezed by electrostatic force to deform with variable length when voltage is applied; the schematic diagram is shown in Figure 3b. Moreover, the Maxwell force is the electrostatic force which is generated between two electrodes under electrification. Due to this, the Maxwell force can achieve motion immediately with electric actuation [63]. However, DE and the Maxwell force both require high voltages to realize function. IPMC is an ionic electroactive polymer which is able to achieve deformation directly with a low actuation voltage based on the energy transfer mechanism of ion migration and its particular structure [64], as shown in Figure 3c. Specifically, an IPMC film consists of a positive electrode, a negative electrode, and an electrolyte. When a high voltage is applied to the electrodes, hydrophilic cations in the electrolyte accumulate at the negative electrode. Based on this, the IPMC film bends towards the positive electrode. The angle of bending is inversely proportional to the thickness of the IPMC film. Moreover, the geometrical parameters of the IPMC film, such as length, width and height, affect the deformation effect. IPMC does have disadvantages, hpwever, such as back relaxation effects. Electric actuation has the advantages of high response and remote control, although there exist problems with electrical breakdown coupling instability and poor safety.

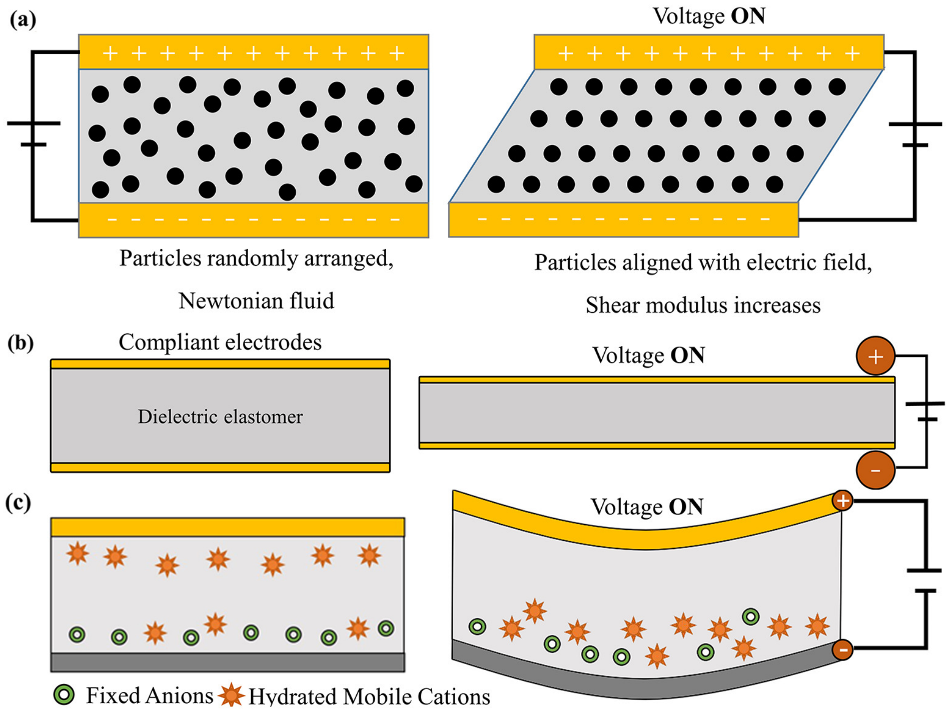

Figure 3. (**a**) Internal dielectric particle transformation of ERF after applying electric field. (**b**) Deformation schematic diagram of DE under voltage. (**c**) Deformation schematic diagram of IPMC under voltage.

2.4. Magnetic Actuation

Magnetic actuation plays an important role in adjusting the stiffness of magnetic-sensitive materials which can achieve deformation under external force by adjusting the magnetic field. Magneto-rheological fluid (MRF) is a magnetic sensitive material frequently used in this actuation; it consists of small soft magnetic particles with high permeability and a non-permeable liquid [65]. The principle of MRF stiffness modulation is based on the viscosity and yield stress of such fluids, which varies with changes in the applied magnetic field. As shown in Figure 4a, randomly distributed magnetic particles in the non-permeable liquid form particle chains along the direction of magnetic field. These particle chains can generate considerable viscosity and increase stiffness.

Compared with MRF, magneto-rheological elastomers (MRE) has better variable stiffness performance; the elastomer does not leak like a liquid does. The microstructure variation of MRE is shown in Figure 4b. MRE can be obtained by simply replacing the liquid medium with elastomers. The magnetic particles in MRE arrange into chains by magnetic fields during the curing process of the elastomers, similar to MRF [66].

Magnetic actuation can conduct manipulation with wireless actuation. However, it is difficult to control motions and force output, and it is hard to achieve precise control with the magnetic field.

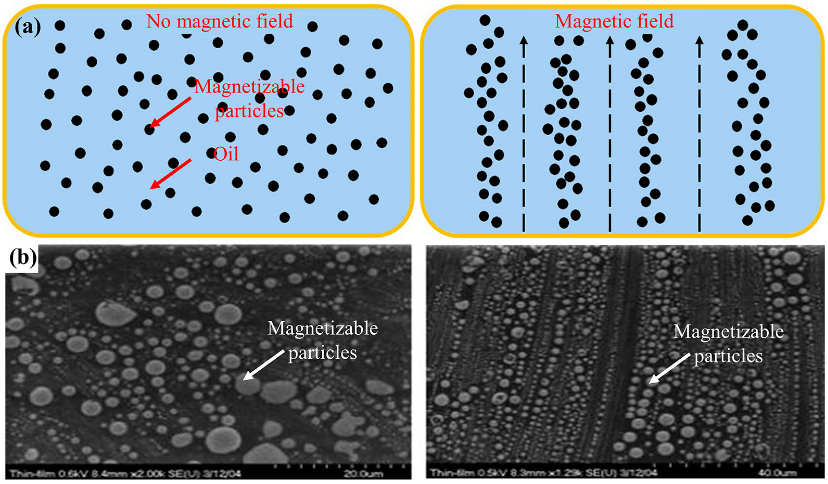

Figure 4. (**a**) Microstructure diagram of MRF. (**b**) Scanning electron microscopy photos of MRE microstructure variation.

2.5. Light Actuation

Light actuation uses an external stimulus to deform the materials via exposure to light. There exist two primary forms of light actuation, namely, photothermal and photochemical actuation, which use different mechanisms. The former is actuated by light-induced temperature transitions, while in the latter photosensitive materials are directly actuated to realize deformation.

Photothermal actuation converts the absorbed light energy into heat energy through the photothermal material in the system; the thermal energy induces the deformation of the polymer material. The photoinduced shape memory polymer material is prepared by introducing photothermal materials into the polymer matrix. This kind of material is essentially a thermally-induced shape memory material. The optical fiber is introduced into the polystyrene matrix to construct a photoinduced shape memory polymer. After the material is shaped, it is irradiated with a mid-infrared laser [67]. The optical fiber converts the light energy into heat energy and induces the material to return to its initial shape. Figure 5a shows the shape recovery of the material at different irradiation times.

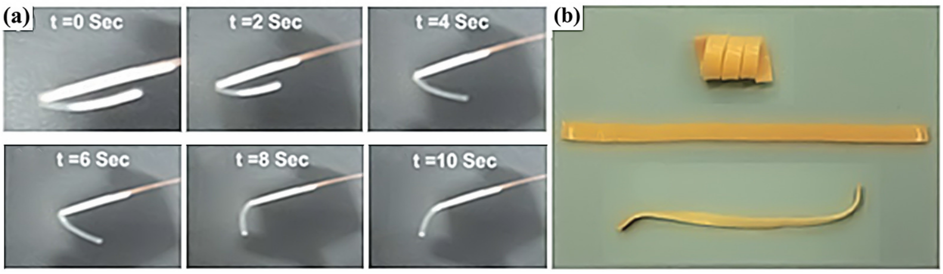

Figure 5. (**a**) Shape recovery of the photoinduced shape memory polymer material [67]. (**b**) Deformation process of photothermal shape memory polymer materials [68].

In addition, photochemical actuation is actuated by a chemical reaction that occurs after illumination. The groups with photochemical reactivity are introduced into the polymer network to construct memory materials, and the materials deform and restore the initial shape via light-controlled chemical changes. For instance, when light is irradiated on one side of the material, the monomer molecules on the irradiated side become crosslinked. This contraction only occurs on the irradiated side, while the non-irradiated side remains unchanged, causing the entire material to undergo deformation [68], as shown in Figure 5b.

Moreover, light actuation can achieve fixed-point actuation by using a small range of light with infinite energy sources. Based on this, wireless actution could be realized without the constraint of connectors. However, there exist problems with slow reaction times, small output force, and poor controllability.

2.6. Humidity Actuation

Humidity actuation is based on the characteristic of moisture-sensitive materials, which can realize internal volume changes by adjusting the environmental humidity gradient to accomplish deformation.

Polymer films are commonly used as moisture-sensitive materials; they achieve deformation by absorbing and releasing water, allowing them to quickly respond to environmental humidity changes and realize bending deformation under the effect of water vapor [69]. A schematic diagram is shown in Figure 6a. Cellulose is able to synthesize cellulose stearates with different degrees of substitution. Cellulose stearates with a low degree of substitution have good humidity response characteristics. Water molecules can be absorbed or released by the cellulose stearate film. Hence, the cellulose stearates can achieve controllable bending and folding movement [70], as shown in Figure 6b.

However, humidity actuation is usually accompanied by relatively difficult control and small output force. It has challenges with accomplishing certain operations, such as load bearing, and is unable to achieve long-term stable actuation performance.

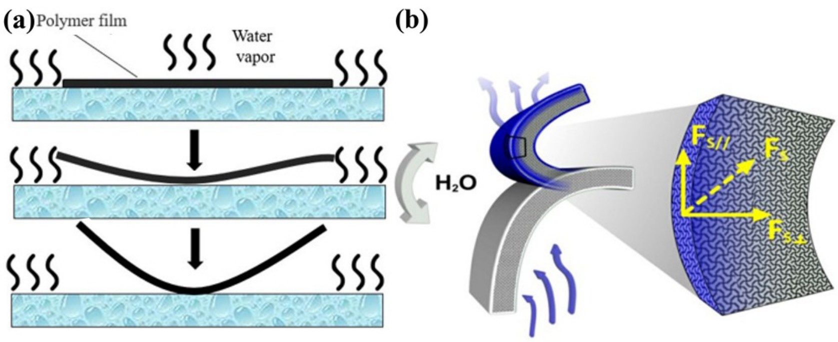

Figure 6. (**a**) Schematic diagram of polymer film with water vapor. (**b**) Schematic representation of cellulose stearate film with the effect of water.

2.7. Chemical Actuation

Chemical actuation is different from other actuations that are actuated by external stimuli. The actuation power comes from the energy generated by combustion or chemical reactions, which is used to achieve motion.

Combustion reactions exhibit dramatic changes and quickly produce a large amount of gas and heat energy, which can be directly converted into mechanical energy for actuation [71]. However, combustion reactions make it difficult to accurately control the resulting motions and improve the robustness due to the multiple factors of combustion. Moreover, chemical reactions may produce gas slowly, and these gases can be accumulated as a gas source to conduct motions [72]. For instance, liquid solvents under catalysis can create a large amount of gas. The chemical reaction of hydrogen peroxide catalyzed by silver produces oxygen; the schematic diagram of this chemical reaction is shown in Figure 7. Chemical actuation is an internal actuation method that can achieve wireless actuation. However, it cannot be active for very long without external energy input, and it is difficult to control the actuation energy.

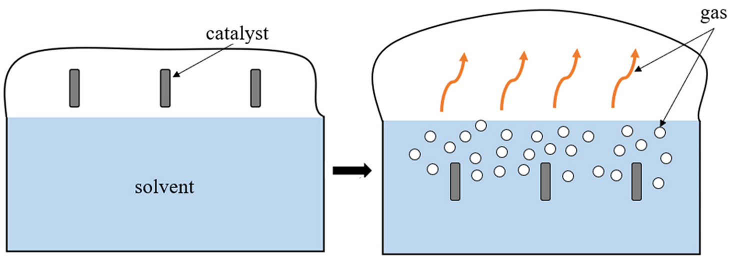

Figure 7. Schematic diagram of the reaction between hydrogen peroxide and catalytic silver.

2.8. Acoustic Actuation

Acoustic actuation provides a new opportunity to implement wireless actuation. Theoretically, acoustic energy could suspend objects in the air or manipulate objects. Hopefully, this potential method can extend the choices available for actuation methods. The principle of manipulation is to use standing waves to form sound traps, which then create suspension forces to resist gravity and keep items suspended [73], as shown in Figure 8a.

Furthermore, acoustic actuation may become a new actuation method through the use of ultrasonics to actuate particular liquids, such as non-Newtonian liquids. When actuated by ultrasonic waves, a non-Newtonian liquid is pushed up and deformed, as shown in Figure 8b. If elasticity or film could be used to limit the deformation of non-newtonian liquid, the actuation principle could be used to actuate a soft actuator in a similar manner to fluid actuation [74].

Table 1 summarizes the advantages and disadvantages of each actuation method. In order to achieve a certain operation or motion, it is important to select the appropriate actuation method to provide actuation energy based on their respective advantages. Furthermore, combining multiple actuation methods may make it possible to overcome the limitations and disadvantages of a single method.

Table 1. Advantages and disadvantages of various actuation methods.

Actuation	Advangtages	Disadvantages	References
Fliud actuation	high energy efficiency, simple structure, flexibility, low cost.	heavy auxiliary equipment, high sealing requirements.	[44–47]
Thermal actuation	contactless actuation, miniaturized actuation.	poor controllability, low actuation efficiency, dependence of intelligent materials.	[48–58]
Electric actuation	high response, wireless actuation, easy integration.	coupling instability of electric breakdown, and poor safty.	[59–64]
Magnetic actuation	remote control without contact.	poor precision control	[65,66]
Light actuation	remote directional wireless actuation.	slow reaction, small output force, poor controllability.	[67,68]
Humidity actuation	wireless actuation.	low precision deformation, poor real-time ability.	[69,70]
Chemical actuation	internal chemical reactions, rapid response.	low precision, poor controllability.	[71,72]
Acoustic actuation	non-contact actuation, direct energy conversion.	small actuation force, complex auxiliary equipments.	[73,74]

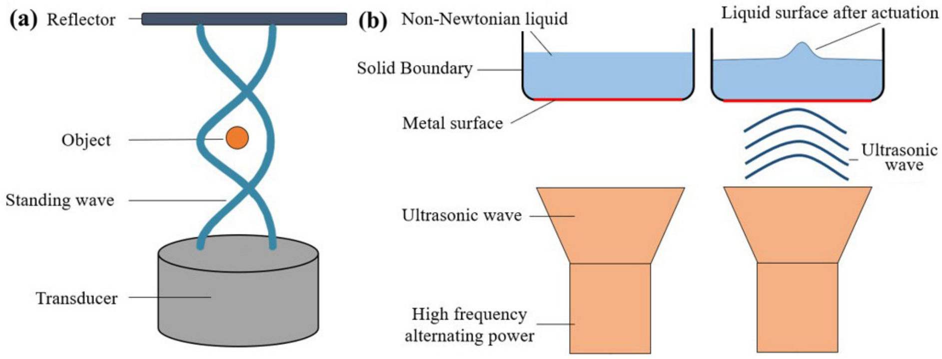

Figure 8. (**a**) Schematic of an object suspended by a standing wave. (**b**) Schematic diagram of a non-Newtonian liquid actuated by an ultrasonic wave.

3. Design

3.1. Bending Motion

By adding non-expansive constraints to flexible materials, bending motions can be achieved under gas pressure. Non-expansive constraints can be preprogrammed at a specific position of the soft actuator to constrain the deformation of the actuator, which can result in uneven stretching to achieve bending motion. An actuator based on a fiber-reinforced structure was proposed in [75] which consists of a soft gas chamber, circumferential winding fibers, and a strain-limiting layer, shown in Figure 9a. The double helix winding fibers around the gas chamber constrain the radial expansion, and the strain-limiting layer at the bottom of the gas chamber limits the elongation of one side of the actuator. The preprogrammed fiber-reinforced structure results in a bending motion towards the strain-limiting layer when inflated. In addition, the angle of bending and the input pressure vary approximately linearly [75]. Compared with a multi-chamber pneumatic bending actuator, this bending actuator had a larger output force, and the bending curvature was constant. Galloway et al. presented a fiber-reinforced soft bending actuator. The bending curvature and axis of the actuator can be programed with a flexible and selective placement of conformal coverings [76]. Ye et al. designed a pneumatic soft bending gripper; the bending motion is generated by using a limiting fiber to replace the axial restraint layer [77]. Deimel et al. proposed a highly compliant bending soft actuator, with the semicircular chamber inside the actuator is fiber-reinforced as well. Bending motion can be achieved due to the decreasing cross-section along the root to the tip [78].

Uneven stretching of a soft structure can be used to achieve a bending motion when pressurized. The expansion of the actuator in the axial direction causes the actuator to elongate unevenly under pneumatic actuation, which leads the actuator to bend in a less elongated direction. A pneumatic networks bending actuator was proposed by Mosadegh et al. [**?**], as shown in Figure 9b. The actuator is based on multi-chamber structure with elastic material, and the parallel chambers are connected by a channel. The inextensible bottom layer acts as a limiting layer, and the asymmetric elongation of chambers and limiting layer induce the multi-chamber to conduct a bending motion when pressurized. Additionally, Shepherd et al. designed a pneumatic network of flexible actuators that bend under inflation due to the decreasing cross-section of the chambers [80]. Based on a number of origami pneumatic networks chambers, Kim et al. proposed a deployable soft actuator. The sides of the chambers are combined with a non-elongable structure, while the axial direction can freely extend under pressure. When the uneven elongation of the side and the axial direction induce the actuator to bend, the origami pneumatic networks chambers rapidly expand and increase the force arm when inflated [81].

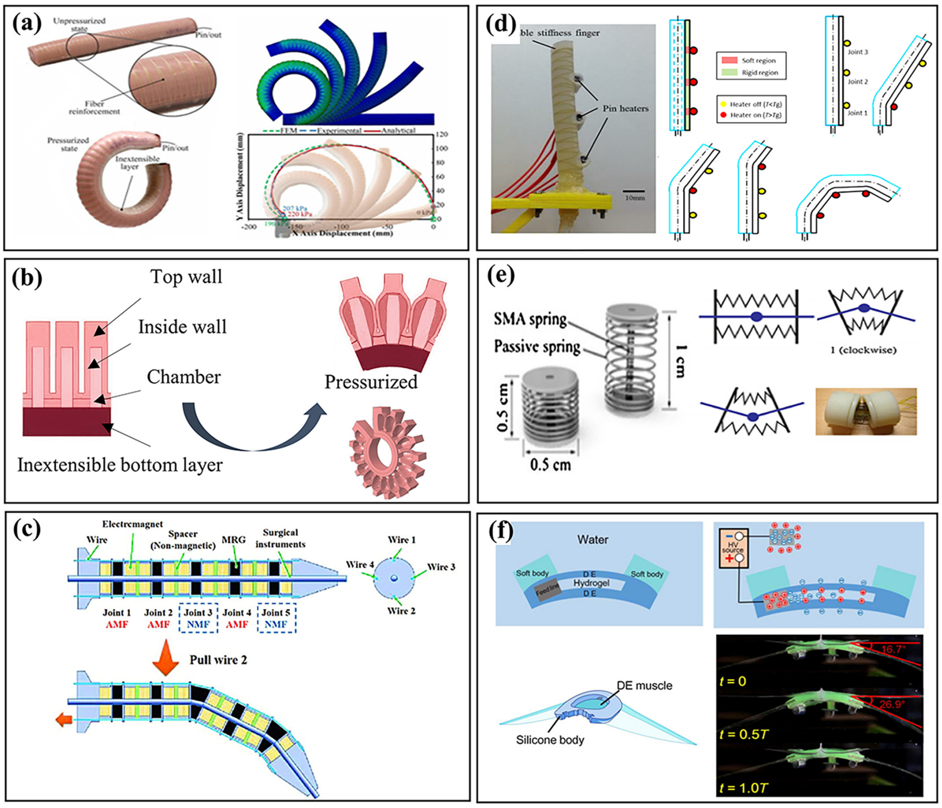

Figure 9. (**a**) The bending motion and finite element analysis of a fiber-reinforced soft actuator [75]. (**b**) Pneumatic network structure and bending posture under pressure [?]. (**c**) Bending motion of the variable stiffness multi-joint actuator [82]. (**d**) Actuator prototype with bending status of each joint [83]. (**e**) Single spring structure and bending posture combining two spring units [84]. (**f**) The internal structure and actuation principle of a bending actuator [85].

In addition, variable stiffness structures can achieve bending motion at the low stiffness point when actuated. By changing the structure stiffness of the actuator parts, the parts with low stiffness first deform under the actuation force. By reasonably designing and arranging the distribution of uneven stiffness, the actuator is able to achieve bending motion. Utilizing intelligent materials, variable-stiffness structures could be more widely adopted in soft actuators. Kitano et al. presented a soft actuator to accomplish bending motion by adjusting joint stiffness based on a magneto-rheological (MR) gel [82], as shown in Figure 9c. The actuator consists of MR gel rings, electromagnets, four uniformly distributed wires, and non-magnetic gaskets. The primary function of the gaskets is to prevent leakage of the magnetic field from affecting the performance of adjacent joints. When a magnetic field is applied to the MR gel ring, the stiffness increases rapidly due to the large variation in gel viscosity. On the contrary, when the magnetic field disappears, the stiffness of the MR gels decreases. Consequently, the MR gel rings become soft joints, which bend under the unbalanced force of the pulling wires. Similarly, Yang et al. designed a soft actuator that could deform in the same way as a human finger [83], as shown in Figure 9d. According to the design, a fiber-reinforced elastomer pastes to a substrate made of SMP. The heaters distribute at the bottom of the SMP substrate. According to the characteristics of SMP [86], the stiffness decreases when heated, and the bending motions happens around the heater when the elastomer is pressurized. In addition, Shintake et al. designed a variable stiffness bending actuator which is actuated by DE, with stiffness controlled by a low melting point alloy (LMPA) [49]. Zhang et al. designed a two-layer actuator which consists of a light-absorbing layer and an active layer [87]. The light-absorbing layer is made up of single-walled carbon nanotube; it absorbs light energy and converts it into heat energy. The active layer consists of a polymer that can expand or contract when heated.

Hence, the bending motion is achieve due to the uneven expansion or contraction of the two-layer structure.

Thus, actuators can accomplish bending motion based on unbalanced force. Unbalanced force generated by smart materials or structural design is distributed on different sides of the actuator by proper structural design, which allows the actuator to deform towards the side with greater force. For instance, a small soft actuator based on an SMA spring was designed by Yuk et al. [84], and is shown in Figure 9e. Two combined springs are distributed on both sides of the actuator. The SMA spring activated by electric current shrinks to 50% of the initial state. In this way, the unbalanced contracting force in the couple of springs induces a bending motion. Similarly, Li et al. designed a soft actuator made up of a pre-stretched dielectric elastomer (DE) and an ionically conductive hydrogel [85], two silicone films are attached to each end of the DE acting as wings, as shown in Figure 9f. The antagonism between the pre-stretched force and Maxwell force generated by the electric field leads to a bending motion. Hence, a bionic fish has been proposed based on this effect which is able to swim underwater similar to fish. However, many bending soft actuators remain in the laboratory stage, and are rarely used in specific task environments due to various limitations, such as insufficient force output and difficulty in achieving precise control.

3.2. Linear Motion

Soft actuators have been presented to achieve linear motion via circunferential or axial winding fibers. Fibers wound to the circumferential or axial surface of the actuator can constrain expansion in the corresponding direction of the actuator to produce stretching in a specific linear direction. McKibben artificial muscles were first proposed to achieve linear motion in the 1950s [88]. The typical McKibben artificial muscle consists of an inner soft tube and a double-helix braided sheath with nonextensible fibers, as shown in Figure 10a. When the inner tube is inflated, the high-pressure gas compresses the inner surface and the outer sheath, which has a tendency to increase its volume. Due to the non-scalability (or high longitudinal stiffness) of the fibers in the woven reticulated sheath, the actuator achieves inner tube elongation as its volume increases. There exists a linear relationship between the input pressure and the stretch length of the McKibben artificial muscles [88]. Homoplastically, Yamaguchi et al. proposed an in-pipe mobile actuator with two clamping units. One is limited axially by fiber and the other, used as the propelling unitm is wound circumferentially [89], as shown in Figure 10b. The propelling unit can elongate in the axial direction when inflated because the circumferential fiber limits the radial expansion. Combined with the clamping units, the propelling unit can realize continuous linear motion. This actuator was able to complete a crawling movement in a pipe by controlling these three units sequentially.

Certain intelligent materials can conduct linear expansion or constriction under external stimulated conditions. Thanks to the properties of smart materials, it is possible for them to stretch under heating or electrostatic forces, which can result in linear motion by combining multiple actuators to amplify tiny stretch deformations in each actuator. Menciassi et al. presented a linear motion soft actuator [90], which is shown in Figure 10c. The actuator consists of a flexible SMA spring, two brass disks, and a silicon shell. The two brass disks are combined in the silicon shell, which is connected to the SMA spring. Contraction of the SMA spring pulls the silicone shell when the Joule effect heats the spring. After the SMA spring cools, the silicon shell is restored to the initial state. Consequently, the actuator can conduct linear motion. The actuator was used as an earthworm to achieve linear peristalsis and bionic movement by asynchronous control. Ni et al. demonstrated a polymer interdigitated pillar electrostatic (PIPE) actuator based on dielectric liquid which achieved an output force density 5 to 10 times higher than natural muscle [91], as shown in Figure 10d. The PIPE actuator consists of chips, dielectric liquid, and springs; each chip has a high density column, while the spring between the chips connects the two parts and provides the restoring force. Notably, the dielectric liquid fills the interspace, which could increase breakdown voltage and electrostatic force. When an electric field is applied, the generated electrostatic force between the two chips pulls the movable pillar array towards the fixed pillar array without changing the pillar space, resulting in linear contraction. After the electric circuit is cut off, the springs are restored to their original position. Meanwhile, larger force output can be achieved by combining multiple PIPE actuators.

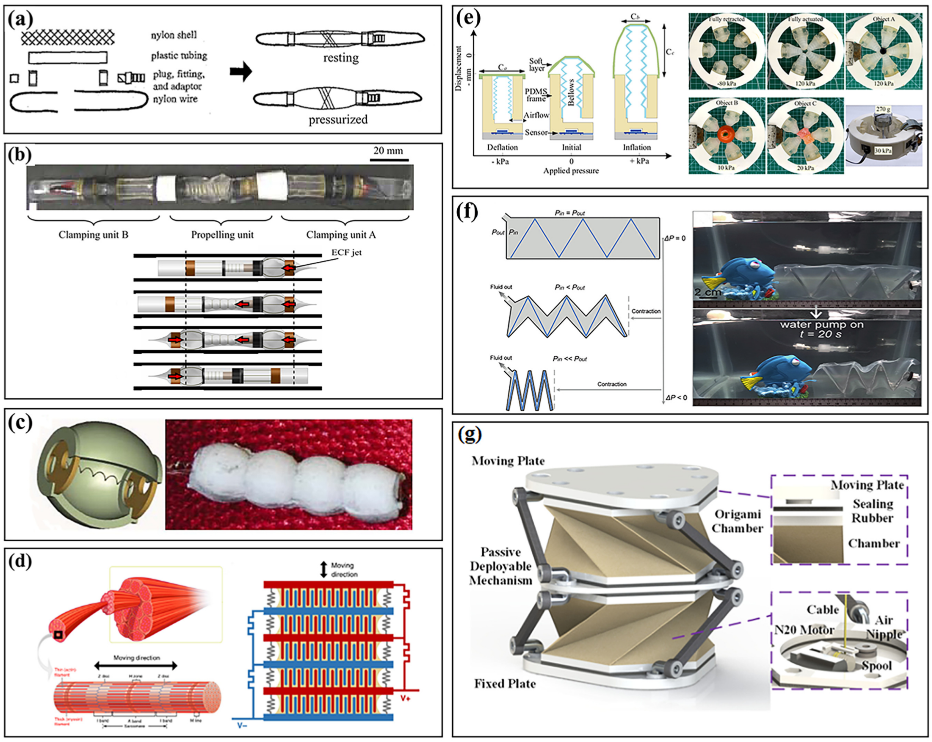

Figure 10. (**a**) The composition structure of McKibben artificial muscle and the forms in two states [88]. (**b**) The in-pipe mobile robot and locomotion of the in-pipe mobile robot [89]. (**c**) The structure of the module and the artificial earthworm prototype [90]. (**d**) Structure of skeletal muscles and stack schematic diagram of polymer interdigitated pillar electrostatic (PIPE) actuators, which are similar to the structure of natural muscles [91]. (**e**) Conceptual model of the bellows-driven soft actuator that represents smooth muscle contractions of a stomach [92]. (**f**) Schematic diagram of the operation of an actuator pulling an underwater fish for 3.5 cm in 20 s [93]. (**g**) Schematic diagram of a pneumatic/cable-driven hybrid linear actuator [94].

At present, many foldable structures are used to achieve linear motion with a symmetrical cross-section, which can produce a telescopic motion in a fixed direction through the design of the crease under the pneumatic or cable actuation. A bellows was used as a kind of foldable structure with a soft actuator to achieve linear motion in [92]. The actuator was able to produce linear motion similar to the smooth muscle in the stomach, as shown in Figure 10e. After gas is infalted or extracted, the top of the bellows is subjected to internal or external gas pressure. Based on this, the bellows can conduct linear motion. Due to circumferential creases, the radial direction has a resistance force that resists the gas pressure, and there is slight radial expansion or contraction; the main change is the axial expansion. Based on the bellows, a soft pneumatic actuator was made and installed in a circular frame to simulate the circular contraction of the stomach. Similarly, origami is one kind of foldable structure with light weight and high efficiency. Based on origami, Li et al. presented an origami-inspired artificial muscle which could realize linear motion like a fish [93], as shown in Figure 10f. The origami structure requires only a foldable skeleton, a flexible skin, and a fluid medium. The linear motion of contraction or elongation is realized by changing the pressure difference between the inside and outside of the artificial muscle. In the initial equilibrium state, the pressure difference between internal and external fluid is zero. When the pressure drops, the external skin produces tension, thus actuating the foldable skeleton of origami to achieve linear motion. Moreover, Zhang et al. designed a pneumatic/cable-driven hybrid linear actuator with a deployable mechanism based on an origami structure [94], as shown in Figure 10g. The structure mainly includes a pneumatic folding room, a cable drive system, and an unfolding mechanism. Pneumatic pressure makes the actuator elongate, and the pulling cable makes the actuator shorten. Bidirectional linear motion is realized through the resistance of the cable and pneumatic pressure. Because an origami chamber has a coupled torsional motion, two folding chambers with reverse torsional motion are used to offset the torsional motion to produce a pure linear flat motion. Notably, the linear actuator contains a passive deployable mechanism with high radial stiffness, which is able to withstand large loads. In addition, Aziz et al. designed a novel coil polymer actuator that could achieve linear motion by converting microwave radiation into thermal stimulation [95]. This spiral rotating actuator is made of high-stretch nylon-6 fibers filled with carbon nanotube (CNT). Under microwave irradiation, the CNTs absorb external electromagnetic energy and convert the energy into thermal energy to heat the fibers, allowing the actuator to achieve linear motion similar to muscle.

3.3. Torsional Motion

Non-uniform stiffness structures of actuators can be designed to achieve torsional motion. Torsional motion can be generated by means of preprogrammed designs, as non-uniform stiffness structures are able to exhibit different deformations under actuation. Gorissen et al. proposed a flexible pneumatic torsional actuator [96] which is shown in Figure 11a. The torsional actuator consists of two identical back-to-back pneumatic airbag arrays; the chambers of thepneumatic airbag are tilted and in a uniform arrangement. When the two pneumatic airbags are inflated separately, the actuator achieves bidirectional torsional motion by actuating two pneumatic airbag actuators separately. Moreover, Xiao et al. designed a torsional pneumatic networks actuator with three spiral chambers distributed on the elastomeric body, which collapse inward cooperatively when negative pressure acts on the chambers, resulting in torsional motion [97]. Analogously, a foldable actuator with non-uniform stiffness could accomplish torsional motion. Jiao et al. presented a foldable bidirectional torsional actuator with creases [98].The crease is obtained by removing part of the material on the surface of the soft actuator. As the thickness of the crease is smaller than the wall thickness, the stiffness at the crease is lower. When the vacuum is extracted, shrinkage first occurs at the crease, and this shrinkage can be used to achieve torsional motion.

An asymmetric actuation force can be generated due to asymmetric distribution of intelligent materials in the preprogrammed structure, resulting in different deformatoins used to achieve torsional motion. Shim et al. designed a torsional actuator composed of an SMA wire embedded in a polydimethylsiloxane (PDMS) matrix [99], as shown in Figure 11b. As the main mechanism of actuation, the SMA wire has torsional strain preapplied. The prestrained SMA wire shrinks during the martensite to austenite phase transformation under Joule heat. The SMA wire then returns to the initial state without torsional prestrain when shinking. Hence, the actuator achieves torsional motion with a large torsional angle. Additionally, when energized under clockwise torsional prestrain, the achieved effect is counterclockwise torsion. Ahnet al. proposed a soft morphing actuator using smart soft composite composed of SMA, PDMS, and acrylonitrile butadiene styrene (ABS) [100]. The actuator achieves torsional motion via the coupling effect of motions induced by the composite. However, these actuators are very small and produce minimal output force.

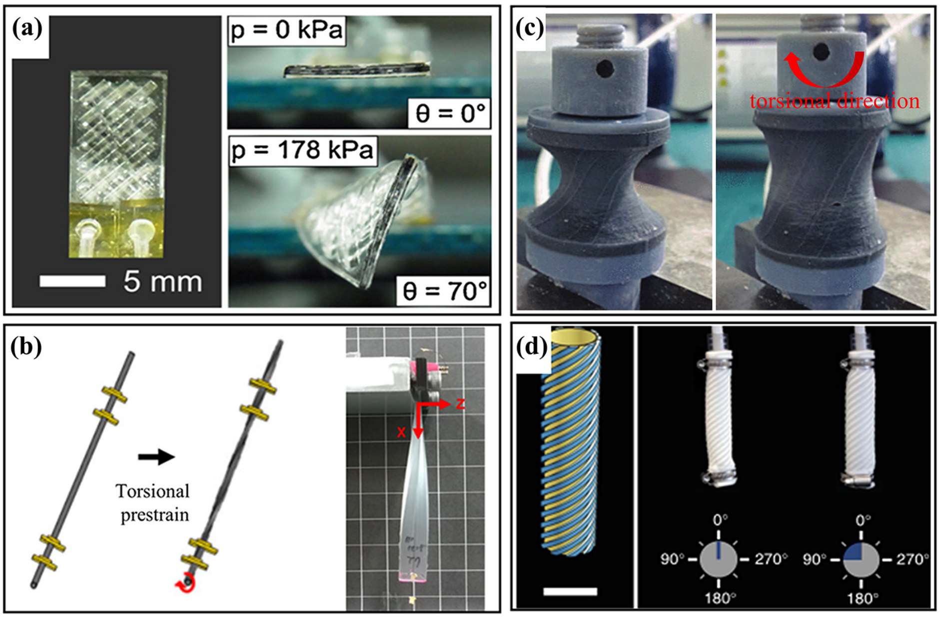

Figure 11. (**a**) Torsional actuator and torsional angles with different pressures [96]. (**b**) Schematic diagram of torsional prestrain and torsional angle of the actuator [99]. (**c**) Process of a pneumatic torsional actuator [101]. (**d**) Model drawing and torsional effect [102].

Asymmetric constraints can be imposed on pneumatic preprogrammed structures to conduct torsional motion. For example, asymmetric constraints with a spiral distribution can be subjected to a stretching force, causing the actuator to produce a torsional motion under the pneumatic actuation. These kinds of architectures can be used to achieve large overall motion and output force. Lee et al. proposed a new pneumatic modular torsional actuator with a spiral constraint added to its surface [101], as shown in Figure 11c. When applied to compressed gas, the actuator module induces torsional motion due to the spiral constraint. However, the torsional deformation of the actuator is not obvious due to the length limitation of the fibers embedded in the actuator. There exists a small angle when the pressure gas is supplied. To improve torsional performance and motion, a torsional actuator was designed by Schaffner et al. [102], as shown in Figure 11d. This actuator can achieve a large torsional angle under pneumatic actuation. Sprial stripes are added to the outer surface of the elastic body and fixed at both ends. When the elastic body chamber is inflated, a torsional motion occurs due to the constraint of the external spiral stripes. In addition, Yan et al. presented an inflatable soft actuator driven by two spiral chambers wound by fibers. This actuator has a purely efficient torsional motion, without any bending or extension movements [103].

3.4. Spiral Motion

Based on the non-uniform shrinkage of intelligent materials, spiral motion can be achieved as well. Non-uniform shrinkage is usually used in bilayer structures. The shrinkage of one layer is usually greater than that of the other layer. When the degree of shrinkage varies greatly, the bilayer structure achieves a spiral motion. Feng et al. designed a bilayer structure to accomplish spiral motion [104], whoich is shown in Figure 12a. The bilayer structure is 3D printed and corresponding self-morphing wire material is polylactic acid (PLA); the stresses of the two layers are in different directions due to different printing patterns. When the bilayer structure is heated to above the glass transition temperature, the upper layer shrinks and the lower layer expands along the printing angle, which leads to self-spiralling behavior. Notably, the right screw and left screw can be controlled by the printing angle. However, this kind of motion is limited by small output force and fewer applications because of the material characteristics.

Furthermore, the coupling effect between different motions can be combined to realize sprial motion. For example, the combination of bending and torsional motion can achieve spiral motion. Hoang et al. designed a variable stiffness spiral gripper [105], shown in Figure 12b. The gripper is mainly composed of a core soft actuator of fluid actuation, fabric sleeves, and a variable stiffness structure. When pressurized fluid actuates the core actuator, a coupled extended torsional motion is generated. Meanwhile, the gripper finger causes a bending motion, with a strain limiting the side of the fabric sleeve. Hence, the gripper is able to accomplish a spiral motion to wind around objects by combining bending and torsional motion.

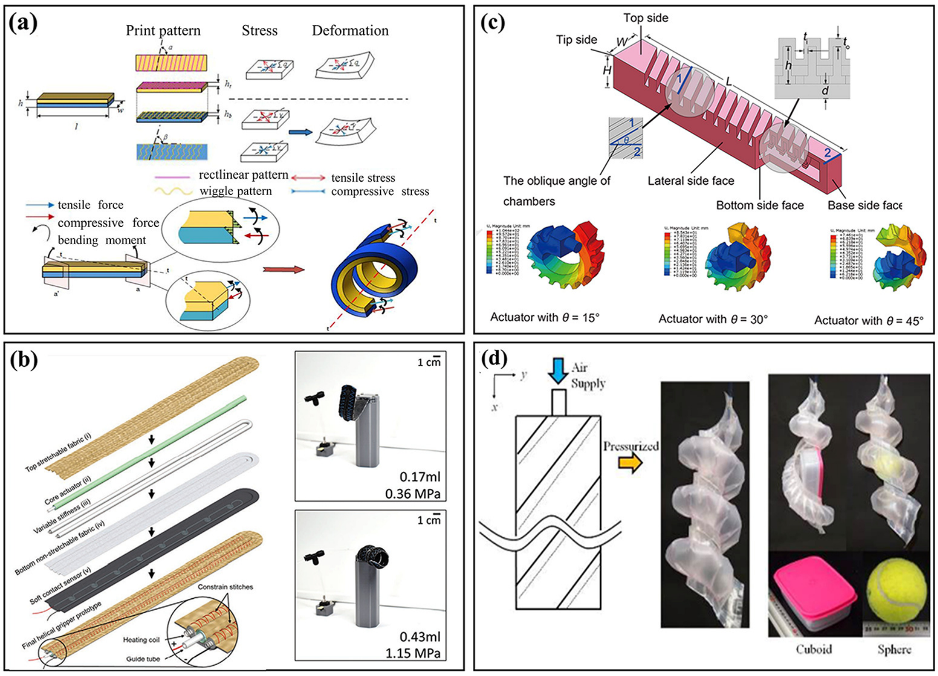

Figure 12. (**a**) Schematic diagram of a bilayer structure under different printing patterns and the principle of deformation [104]. (**b**) Structure of a spiral actuator and spiral deformation posture [105]. (**c**) Structure diagram of an actuator and spiral posture under different pressures [106]. (**d**) Structure diagram of actuator and spiral effect [107].

In addition, a preprogrammed asymmetric structure can be used to accomplish spiral motion. A tilted chamber design allows the actuator to elongate in the vertical direction of the tilted angle. Due to the existence of constraints, spiral motion can be achieved under pneumatic actuation. Wang et al. proposed a spiral gripper by designing asymmetric inclined chambers [106], as shown in Figure 12c. Chambers with a certain inclination angle expand via inflating the high-pressure gas; the expansion direction is perpendicular to the inclination angle of the cavity, which accomplishes spiral motion of the winding objects. Alternatively, soft actuators can realize spiral motion by using a plastic film to obtain better grasping force. Compared with an actuator made of elastic material, a folding plastic film can result in a lightweight soft actuator which is suitable for the human body to wear and has enough durability for use. Amase et al. presented the spiral gripper [107] shown in Figure 12d. The gripper consists of two layers of plastic film. The upper layer is folded obliquely to produce creases, then the two layers are connected by thermal welding. When inflated, the gripper realizes a spiral motion, and can automatically change its shape according to the shape of the object.

3.5. Composite Motions

The actuators above are only able to conduct a specific motion when actuated, which is not suitable for complex tasks. Therefore, actuators that can achieve composite motions attract more attention. For multi-module actuators, each module is able to achieve different motion, and composite motions can be realized by combining multiple modules. Due to pneumatic artificial muscles and external fiber constraints, Guan et al. designed a kind of actuator that could be assembled modularly [108], as shown in Figure 13a. Pneumatic artificial muscles achieve elongation and contraction, while bending and spiral motion are achieved by adding parallel axial and helical cables; then, by combining various bending and spiral actuators, the result is a combined actuator that can conduct complex composite motions, similar to an elephant's trunk.

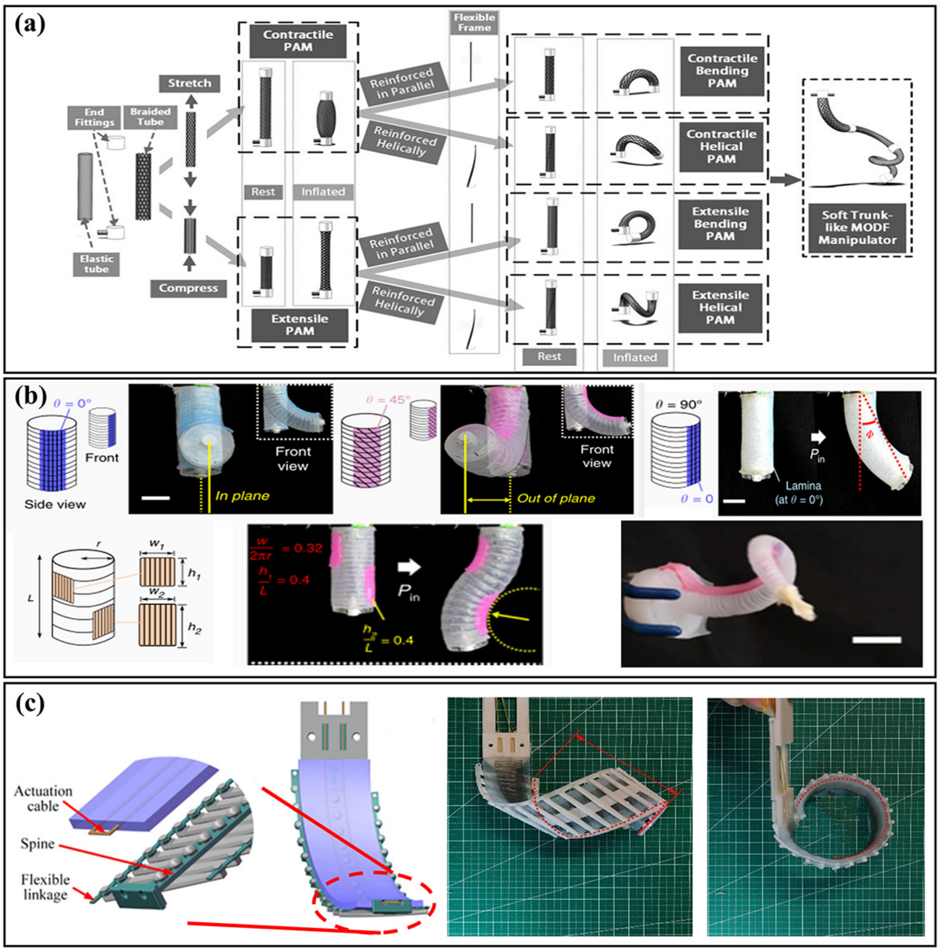

Figure 13. (**a**) The realization process of pneumatic artificial muscle composite motions [108]. (**b**) Motion effects of three angle fiber direction composite laminae adhered on a soft actuator [109]. (**c**) The mechanism of a scaffold reinforcement soft actuator and the effect of different motions by changing the scaffold direction [110].

More dexterous motions can be accomplished by dynamically adding external constraints. These dynamically added constraints can make the actuator achieve specific deformations, which can then be combined to achieve more complex motions. Kim et al. presented a self-adhesive composite laminate [109] which was able to adhere to any volume-expanding soft body to control its trajectory. Due to the unidirectional embedding of non-expandable continuous fibers in the hyperelastic matrix of composite laminates, these composite laminates can only be stretched in one direction. The soft actuators can deform specific trajectories according to their design by simply adhering laminates to their surfaces. Moreover, self-adhesive composite laminates have multiple fiber orientations to achieve bending or spiral movements by adhering, such as 0, 45°, and 90°fiber orientations. Figure 13b shows the various motions after adhering laminates on the surface of such a soft actuator; the composite laminates can adhere to any place in order to achieve motion.

These variable-constraint structures can be used to increase the precise control and motion diversity of organisms. Target motion effects with high application significance could be achieved by adjusting the constraints.

In addition, such reprogrammed structures could be used to realize different kinds of motions, which would then adjust the distribution of the constraints on the actuator and could achieve different deformations, such as bending and spiral motions. Recently, Jiang et al. proposed a soft gripper consisting of a soft layer and a rotatable scaffold reinforcement layer, where the scaffold reinforcement layer is distributed on the surface of the soft gripper [110], as shown in Figure 13c. The actuation cable is inside the soft layer, while the scaffold layer is made of a spine and flexible linkages. The direction of the scaffold can be adjusted by controlling the cable, which in turn can change the motion constraint of the gripper, resulting in different motion forms. By dynamically adjusting the direction of the scaffold, the bending motion and complex spiral motion of the soft gripper in three-dimensional space can be accomplished via the actuation cable.

A structure design matrix is proposed to summarize existing implementations of various motions through different actuation methods and design approaches, as shown in Table 2. To the best of our knowledge, actuators able to conduct certain motions under specific actuation have not yet been reported in literature. Designs of the corresponding actuators could refer to structures of actuators under similar actuation methods. For instance, actuators under chemical actuation have not been reported to achieve torsional motions. Because chemical actuation usually makes use of the gas generated in chemical reactions to pressurize actuators, the actuator structures under fluid actuation, such as tilted multi-chamber and external spiral constraints, could be referenced to design torsional actuators under chemical actuation.

Table 2. Structure design matrix based on actuations and motions.

Actuation \ Motion	Bending	Linear	Torsional	Spiral
Fluid	Uneven constraints, Asymmetric stretching.	Fiber-reinforcement, Uniform constraints, Foldable structure.	Multi-chamber, Asymmetric constraints, Uneven elongation.	Tilted multi-chamber.
Thermal	Variable stiffness, Non-uniform stiffness.	SMA spring structure.	Torsional prestain.	Bilayer uneven shrinkage.
Electric	Variable stiffness structures, Unbalanced force.	Linear stretching materials.	/	/
Magnetic	Variable stiffness structures.	/	/	/
Light	Non-uniform shrinkage.	/	/	Non-uniform shrinkage.
Humidity	Internal small volume variation.	/	/	/
Chemical	Uneven volume expansion.	/	/	/

In addition, the materials used in soft actuators are an important part in the design and manufacture of actuators. Different materials have different characteristics and limitations. While many soft actuators use the unique characteristics of smart materials to achieve certain deformations, certain smart materials have certain limitations and shortcomings. Table 3 shows the characteristics and limitations of a number of common materials.

Table 3. The characteristics and limitations of commonly used soft materials.

Materials	Characteristics	Limitations
Flexible silicone	High expansion coefficient, Long lifetime, Good flexibility and safety.	Long molding time, Complex production method, Expensive.
SMA/SMP	Rich phase transition phenomenon, Excellent shape memory and super elastic property, Good mechanical property, Corrosion resistance.	Complex manufacturing process, High-cost.
MRF/ERF	High boiling point, Low freezing point, Large viscosity change, Good chemical stability, Low-cost.	Poor sedimentation stability.
MRE	Large viscosity change, Good stability, Good sedimentation.	Insufficient liquidity.
DE	Large deformation and fast response, Light weight, High energy density.	High actuation voltage, Low safety.
IPMC	Low driving voltage, Fast response, Low power consumption, Low density and good flexibility.	Back relaxation effects, Low control accuracy.

4. Manufacturing

4.1. Shape Deposition Manufacturing

Shape deposition manufacturing (SDM) is another rapid manufacturing method; after rapid prototyping, it adopts a unique method of adding and removing materials [111–114]. Meanwhile, different methods can be introduced according to the materials used for the parts, making it possible to integrate multiple materials into a single actuator [115]. As shown in Figure 14a, through multi-step deposition and removal of materials, multi-material soft actuators with certain outer shapes and internal structures can be obtained. Moreover, rigid electronic components such as sensors can be embedded in soft materials, which provides soft actuators with a flexible appearance and avoids the confines of rigid materials. Currently, SDM has been widely used in soft actuators manufacturing due to the advantages of low cost, simplicity, and a relatively speedy manufacturing process [116–119]. Similarly, the silicone-molding method and SDM manufacturing method have many common characteristics. The silicone shape can be formed by designing the mold, and the soft actuator can be manufactured by multi-step silicone-molding [120,121].

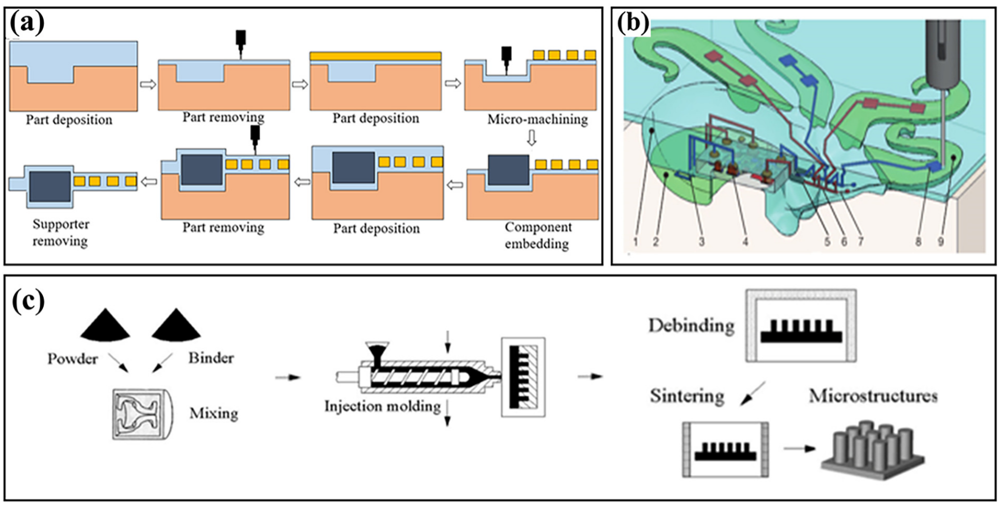

Figure 14. (**a**) Schematic diagram of SDM processes [115]. (**b**) Fully soft robot manufactured by 3D printing [122]. (**c**) Processing steps of micro-powder injection molding [123].

4.2. Three-Dimensional Printing

Three-dimensional (3D) printing is a kind of rapid prototyping technology, sometimes known as additive manufacturing. It is a technology that uses adhesive materials to print objects layer by layer based on digital model files, which is suitable for printing complex structures [124–127]. In the process of printing, the influence of various parameters needs to be considered [128–130]. Early 3D printing technology could only print rigid materials; soft materials were not available in the past, as only thin film parts could be printed due to the viscosity and fluidity of the materials. Wehner et al. made a breakthrough in moving research from semi-soft to fully soft robots [122], as shown in Figure 14b. Using multi-material 3D printing technology, they developed a soft octopus robot able to craw and swim.

4.3. Micro-Powder Injection Molding

Micro-powder injection molding is a new forming technology which combines traditional powder metallurgy technology with modern plastic injection molding technology. It is widely used to produce products with small size and complex shape; therefore, it has been introduced into soft robots as a promising molding method [123]. Soft materials are injected into a mold with a specific shape, then the desired soft parts are obtained through demolding and sintering, as shown in Figure 14c. This method makes it easy to manufacture soft parts with small size [131–134]. However, various defects, such as cracks and bubbles, may appear during the production process. In addition, various parameters which may affect the final molding effect need to be considered, such as the mold temperature, injection pressure, and pressure holding time.

4.4. Soft Lithography

Soft lithography, or soft etching, is a fundamental technology applied to fabrication and microfabrication. It utilizes stamps or molds made from PDMS with microscopic patterns on the surface to achieve microstructure replication by molding and embossing elastomers on a mold [135]. Soft lithography is characterized by replacing the hard mold used in lithography with an elastic mold; thus, it is able to produce more complex three-dimensional structures. In addition, it can change the chemical properties of the material surface as needed, which provieds an opportunity to fabricate multimaterial soft robots [80]. Currently, soft lithography is widely used in optics, biotechnology, microelectronics, sensors, and micro-total analysis systems.

5. Applications

5.1. Wearable Devices

Wearable devices is a general term for a class of products attached to or worn on users as wearable technology, and is commonly used in monitoring and medical fields. Such devices have to be flexible, lightwight, portable, and able to output relatively large torque when used in the medical assistant field. As a result, soft robots are quite suitable for wearable device because of their high compliance, adaptiveness, and safety in human–machine interaction [136,137]. For example, a fluid-driven exoskeleton is designed to be worn on the limb and help disabled people with rehabilitation training, such as standing up independently [138]. Moerover, a flexible exoskeleton with a control system was designed to assist people with walking [139]. However, this flexible exoskeleton cannot provide enough output force and support, making it only suitable for people with a certain level of walking ability. In addition, origami structures have been applied to wearable devices; because of their light weight, actuators made from origami structures can help people who have lost the ability to grip objects with certain weight and size through pneumatic actuation [140]. Furthermore, a low-cost soft neuroprosthetic hand was designed by [141]. In addition to achieving precise movement, the soft neuroprosthetic hand was able to realize particular tactile feedback. Amputees are able to gain real-time feedback from the prosthetic hand, whcih is suitable to wear with only 256 g.

5.2. Exploration and Rescue

Over the past decades, robots have drawn more and more attention in the field of exploration and rescue. Because the working environment is full of complexity and uncertainty, robots must have good anti-damage ability and be able to work normally in an unstructured environment. In addition, they must be miniaturized and lightweight as much as possible in order to meet the requirements of working in a narrow space. Therefore, soft robots have become a research hotspot because of their good environmental adaptability and portability. One example is a novel soft robot able to grow tens of times longer when pressure is applied to its tip, which invests itself with good obstacle avoidance and high load capacity (100 kg) [142]. Cameras and sensors that installed on such robots can achieve real-time transmission of images and signals, which helps them to achieve turning and automatic obstacle avoidance by adjusting the gas flow, which could be useful in earthquake rescue applications. Furthermore, a team from Zhejiang University designed a wireless self-powered soft robot that could be used for deep-sea exploration [143]. Their robot has been tested in the Marianas trench and South China Sea, proving that it can be used in deep sea exploration thanks to its excellent pressure resistance and swimming performance. In addition, soft robots can be used underground. For instance, an underground exploration soft robot has been invented that can burrow in sand at a speed of 480 cm/s [144]. It is used as a carrier for electric wires and irrigation pipes because of its hollow structure and ability to move around and flex under obstacles.

5.3. Industrial Field

Although traditional rigid robots are able to complete automatic operations accurately and efficiently, they may cause potential harm to people because of their rigid structures; in addition, they have shortcomings when dealing with fragile and delicate objects. Therefore, soft robots have attracted much attention in industry because of their good shape adaptability and flexibility [145–152]. One example is a soft gripper based on pneumatic networks that is able to grasp and manipulate objects with complex shapes thanks to its ingenious structural design [106]. Another example is a soft gripper inspired by an octopus that is capable of grasping target objects underwater and in the air through the force provided by suction discs on the gripper or the deformation of the gripper, which has good grasping ability by combining the two approaches [**?**]. A gripper that utilizes particle interference has been designed as well [154]. Coffee beans were inserted into a spherical elastic film to adapt to the shape of objects and variable stiffness grasping was realized by controlling the pressure in the film, with a greater vacuum resulting in higher stiffness. Moreover, a palm with three fingers has been developed that can actively deform to grasp objects with different shapes, which expands the application of soft robots [155]. Additionally, a soft gripper with less control and sensory ability was proposed that is able to manipulate objects without knowing their precise position, shape, or size, including unscrewing caps and sorting snacks [156]. In addition, various hardware facilities can be combined to expand the application of soft robots [157], and grippers assembled on mechanical arms could be used in various industrial tasks.

6. Conclusions and Prospectives

This paper reviews the state-of-the-art research on soft actuators. The principles of various actuations are first summarized. Then, we review different kinds of structural designs used to achieve different motions, such as bending, linear, torsional, spiral, and composite motions. Existing research on manufacturing is discussed, and applications in wearable devices, exploration and rescue, and industrial fields are presented. A variety of actuation methods and motions exist. For different actuation methods, it is necessary to design a suitable preprogrammed structure which controls the deformation of the actuator material in order to achieve a specific motion. The structural design matrix we propose can provide a guide to actuator designs.

Although significant progress has been achieved in soft actuators over the past few decades, many challenges remain in developing soft actuators; these include poor self-healing, low sensory integration, and small region of actuation force. Therefore, soft actuators are expected to improve in the future thanks to their high safety, good controllability, high integration and good repeatability. Meanwhile, the theoretical model of the soft actuator is difficult to model. Non-model behavioral motion control could become a future research direction for researchers; alternatively, other advanced control technologies, such as neural networks, could be used to obtain adaptability to the environment. Furthermore, research of bionic intelligent control algorithms of soft robots should be strengthened. By effectively calculating and controlling the movement, body stiffness, and deformation of soft robots, they could be made to better adapt to changing environments.

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