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REVIEW

Fluid-driven artificial muscles: bio-design, manufacturing, sensing, control, and applications

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Abstract

Developing artificial muscles that can replace biological muscles to accomplish various tasks is what we have long been aiming for. Recent advances in flexible materials and 3D printing technology greatly promote the development of artificial muscle technology. A variety of flexible material-based artificial muscles that are driven by different external stimuli, including pressure, voltage, light, magnetism, temperature, etc., have been developed. Among these, fluid-driven artificial muscles (FAMs), which can convert the power of fluid (gas or liquid) into the force output and displacement of flexible materials, are the most widely used actuation methods for industrial robots, medical instruments, and human-assisted devices due to their simplicity, excellent safety, large actuation force, high energy efficiency, and low cost. Herein, the bio-design, manufacturing, sensing, control, and applications of FAMs are introduced, including conventional pneumatic/hydraulic artificial muscles and several innovative artificial muscles driven by functional fluids. What's more, the challenges and future directions of FAMs are discussed.

Keywords Artificial muscles · Fluid · Bio-design · Manufacturing · Sensoring · Control

Introduction

Nature has long been an inspirational source of the technological growth for humans. The prominent role of nature-inspired concept has been increasingly recognized by scientists and engineers in the past several decades, especially for the biological inspiration. Biological muscle is the actuation type of animals and humans. As a very popular focal point of biological inspiration, artificial muscles that are expected to mimic the biological muscles to actuate the devices or robots have incrementally become one of the research focuses [1–6]. Generally, the artificial muscle is an actuator that can produce linear movements, complex multiaxial actuation, or even controllable motions with multiple degrees of freedom (DOFs), etc. Recent advances in flexible materials (such as hydrogels, electroactive polymers (EAPs), shape memory alloys (SMAs), electroactive ceramics) enable the artificial muscle to possess the softness of biological muscles, which is useful when the machines or robots should interact with human or fragile objects. To date, a variety of artificial muscles, which can be driven by different external stimuli such as pressurized fluids [7–9], thermal energy [10–12], light signal [13, 14], magnetic field [15–17], and electric field [18–21], have been developed, and some typical representatives are shown in Fig. 1. All these existing artificial muscles have their strengths and limitations. For instance, artificial muscles made of SMA are capable of reverting to its memorized shape on heating, which provides large actuation force and high-power density [22–27]. However, their drawbacks, such as unpredictable deformation, slow frequency response, high cost, hinder their widespread application. Electroactive ceramics have also been explored in the area of artificial muscles. Generally, they have rapid response speeds, but their poor deformation capabilities (strain $< 1\%$) and brittle properties have impeded their broad applications. Artificial muscles made of EAPs have attracted much attention in recent years, which could generate deformation when stimulated by an electric field [28, 29]. Typically, there are two types of EAPs based on different deformation mechanisms: electronic (e.g., dielectric elastomers, ferroelectric

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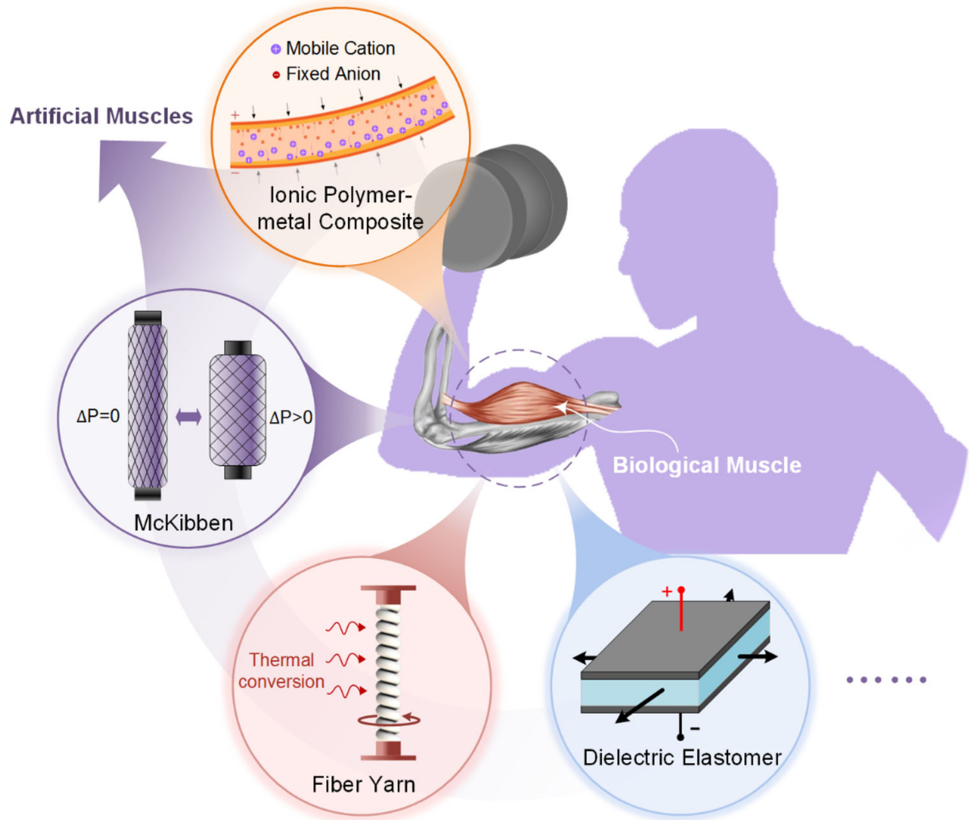

Fig. 1 A variety of artificial muscles have been explored for mimicking biological muscles, and notable examples including ionic polymer-metal composite (IPMC), McKibben muscles powered by pressurized fluid, twisted microfiber yarn based on thermal conversion, dielectric elastomer (DE)

polymers, liquid-crystalline elastomers, etc.) and ionic EAPs (e.g., ionic polymer-metal composite, conducting polymers, etc.). The electronic EAPs exhibit considerable deformation, high energy density, and rapid response speed, but they generally require high activation electric fields (> 150 V/mm) [30–33]. In contrast to electronic EAPs, the ionic EAPs can achieve large deformation with a relatively low electric field (< 10 kV/m) [19, 34–36]. Nevertheless, they have to operate in wet conditions in the solid electrolyte and thus require encapsulation or protective layer in open-air conditions. Low-cost polymer fibers also make a profound impression in the field of artificial muscles [37–40]. Artificial muscles made of polymer fibers mostly exhibit thermal expansion behavior that could contract in length while expanding in diameter, which could generate large stresses up to 140 MPa (4.5% stroke) and significant tensile strokes up to 49% (1 MPa load) [41]. However, the efficiency of these artificial muscles is close to 1%, which brings a great challenge for energy saving. Besides, as the thermal activated artificial muscles, they have a relatively lengthy thermal conversion process during actuation and relaxation and thus lack good controllability.

Among all artificial muscles, fluid-driven artificial muscles (FAMs) are the most prevalent owing to their high energy efficiency, simple mechanism, compliance, durability, and low cost. FAMs work by shifting pressurized fluids between flexible chambers to achieve the force and displacement output. According to different fluid mediums, FAMs could be divided into pneumatic (i.e., pressurized gas-driven) artificial muscles (PAMs) and hydraulic (i.e., pressurized liquid-driven) artificial muscles (HAMs). The pressurized fluids are usually generated using conventional motor-driven pumps or compressors, but these methods increase the weight and volume of the FAMs and thus reduce their portability. To achieve better portability, the fluids that could be pressurized by external stimulus have been increasingly studied, such as thermal energy, electric fields, chemicals, and magnetic fields. Although these stimuli-responsive FAMs have their advantages, they still have great challenges to be widely used in practice applications. To obtain robust, inexpensive, and high-performance artificial muscles, scientists and engineers have made a lot of efforts in this field and reported a lot of remarkable work. To date, many remarkable reviews that focus on a variety of artificial muscles have been published, which offer an overall perspective for artificial muscle [1, 4, 42–46]. However, when it comes to FAMs, including PAMs, HAMs, and FAMs powered by novel methods (e.g., combustion, phase transition, functional fluids, etc.), there is a lack of a comprehensive overview to introduce the different aspects of FAMs. This review is intended to provide a useful reference for those who are planning to get on board FAMs research or apply FAMs to their ongoing research.

In this work, a state-of-the-art review is conducted to summarize the existing researches of FAMs, including conventional PAMs and HAMs such as McKibben muscle and some innovative artificial muscles driven by functional fluids. The design, manufacturing, modeling, sensing, control, and applications of FAMs are introduced, respectively. At the end of this review, the persistent challenges and future direction of FAMs are discussed.

Design

Biological organisms, especially humans and animals, exhibit many extraordinary abilities over the eons of evolutionary, such as the inherent compliance, strong athletic ability, camouflaging ability, or large force output. Scientists and engineers usually take inspiration from these abilities to incorporate biomimetic technologies into their designs of products. Likewise, many bio-inspirations have been integrated into the design of FAMs to obtain the desired actuation. In this section, the bio-inspired design of FAMs is discussed based on their different actuation types, including linear actuation, bending actuation, and torsional actuation.

Linear FAMs

FAMs with the function of linear actuation are designed to directly mimic the contract motion of biological muscles. As shown in Fig. 2, in an antagonistic muscle pair as one muscle contracts the other muscle relaxes so as to obtain bidirectional movements. These biological muscles generally consist of many muscle tissues bundled together and surrounded by epimysium, which use adenosine triphosphate (ATP) to power the contraction movement, generating a force on the objects. In order to reproduce the similar property of biological muscles in artificial counterparts, scientists and engineers have developed a number of linear FAM, including PAMs and HAMs. The basic principle of these FAMs is that the desired linear movement is achieved by inflating the elastomer actuator with pressurized fluids. However, different from the biological muscles that only contract but not expand since the tendon slacks when they expand, these FAMs can generate forces in two directions, i.e., construction or expansion.

To date, the structures of existing linear FAMs are developed based on several different design strategies. The first is bellow-type actuators with symmetric corrugation, as shown in Fig. 3a. The basic principle of this FAMs is that the angle of the folds in the bellow changes when pressurized fluid is supplied to the bellows, thereby achieving the vertical linear motion [47]. Compared to actuators where the elastomer material must strain to generate motion (e.g., fiber-reinforced actuators), this unfolding design places less strain on the material, which could increase the longevity of the actuator and lead to lower operating pressures, whereas this bellow-type design brings a challenge for molding the inner geometry.

Different from the bellow design, the braided or netted artificial muscles, such as the famous McKibben muscle, are more popular and mainstream design in linear FAMs, which consist of an elastic membrane surrounded by sleeving. The elastomer membrane compresses laterally against the sleeve when pressurized fluid is supplied. Consequently, the internal pressure is balanced by braid fiber tension and the radial expansion is translated into linear contraction. So far, many braided- or netted-type muscles have been developed and used in a large range of applications through different actuation types (e.g., pneumatic, hydraulic, ECF, combustion, etc.). For instance, the well-known McKibben muscle is a class of braided PAMs, which was invented by physician Joseph L. McKibben to help the movement of polio patients in the 1950s [48]. Typically, they consist of an inflatable inner tube/bladder inside a braided mesh, of which the tube membrane and braided mesh are both attached to fittings at both ends. When the inner bladder is pressurized to achieve expansion, the geometry of the mesh acts like a scissor linkage, and this radial expansion will be transformed into a linear contraction.

In addition to conventional pneumatic or hydraulic McKibben muscles, Yokota et al. have developed a McKibben-type muscle-like artificial muscle using electro-conjugate fluid (ECF), as shown in Fig. 3b, which can directly convert electrical energy into mechanical energy of fluid inside the artificial muscle to achieve the contraction or restoration movement [49]. The main contribution of this artificial muscle is to make the system tiny and thus greatly improve the portability of artificial muscles because a bulky power source is not needed. Besides, Yamaguchi et al. built an in-pipe mobile robot using ECF fluids based on asynchronous linear motions of two clamping units, where the tube of the clamping artificial muscle is reinforced with fibers along its axis, as shown in Fig. 3c [50]. Notably, the linear actuation of the braided or netted FAMs could also be achieved by using magnetically induced liquid-to-gas phase transitions. Mirvakili et al. presented an untethered McKibben-type artificial muscle that can generate an axial contractile strain and radial expansion through liquid-to-gas phase transitions under a high-frequency (150 kHz) magnetic field, as shown in Fig. 3d [51]. In spite of its widespread use, the braided or netted muscles have several weak points. Specifically, these artificial muscles have substantial hysteresis owing to dry friction between the braid and the tube, which has an adverse effect on artificial muscle behavior and necessitates the use of complex actuator models and control. Besides, the deformation of the rubber tube reduces the generated force because of the deformation energy it stores.

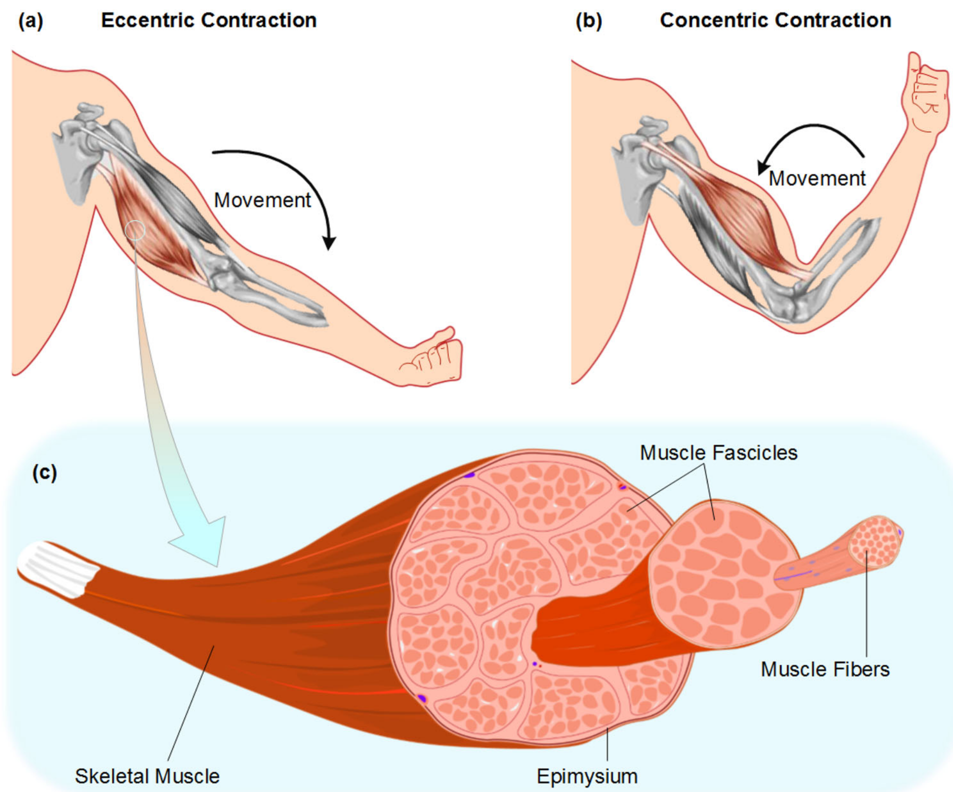

Fig. 2 The working principle of biological muscle. Bidirectional movements based on antagonistic muscles: **a** eccentric contraction and **b** concentric contraction; **c** the schematic of muscle tissue. Skeletal muscle fibers are organized into bundles called fascicles, and the groups of fascicles are surrounding by epimysium

Additionally, an alternative linear FAM called Peano has been firstly developed by Sanan et al. [52], which consists of several tubes arranged serially. Subsequently, a number of Peano fluidic muscles are reported to achieve linear actuation [53, 54], and a typical Peano FAM is shown in Fig. 3e. Notable examples include a Peano actuator developed by Hiramitsu et al., in which it is free of air compressors, valves, nor air supply hoses through the reversible chemical reaction of water electrolysis/synthesis using a polymer electrolyte fuel cell [55]. Similar to McKibben muscles, Peano muscles have the ability to create the high forces of biological muscles with the low threshold pressure but in slim and easily distributed form.

Alternatively, the pleated artificial muscle is another type of linear FAMs that was conceptualized and produced by Daerden and Lefeber [56]. Typically, the pleated muscles composed of a cylindrical membrane with both high tensile stiffness and high flexibility, and the elastomer membrane is uniformly packed together in folds along the axial direction, as shown in Fig. 3f [57]. When pressurized fluid is supplied, it expends by unfolding these pleats and no fraction occurs in this process. Thus, pleated artificial muscles have less energy consumption on the deformation of the tube and are not bothered by friction-related hysteresis.

Except for the aforementioned four types of linear FAMs, other notable designs have also been proposed to produce linear actuation. Li et al. presented a kind of fluid-driven origami-inspired artificial muscles, in which the muscle system consists of a compressible solid skeletal structure, a flexible fluid-tight skin, and a fluid medium, as shown in Fig. 3g [41]. The contraction movement of this artificial muscle is mainly driven by the tension force of the skin that was produced by the pressure difference between the internal and external fluids.

Bending FAMs

In nature, humans or animals are capable of grabbing objects or achieving locomotion via the bending motions of their flexible fingers (e.g., human), tentacles (e.g., octopus), trunk (e.g., elephant), or their soft body (e.g., snake). Inspired by this, scientists and engineers have been tried to design FAMs that can generate bending actuation, thereby endowing the robotic system with the ability to grasp, locomote, or swim. For instance, a kind of octopus-inspired pneumatic robotic tentacle has been reported, which can grab the specific objects with complex rough surfaces [58]. A jellyfish-like pneumatic soft robot has also been explored, which can realize rapid vertical motion underwater via bending deformation of FAMs [59]. Likewise, Frame et al. have constructed a unique soft robotic jellyfish with hydraulic network actuators [60]. Generally, the strategies of producing bending deformation of FAMs to achieve functional gripping or locomotion can be roughly concluded as three groups: (1) selectively pressuriz-

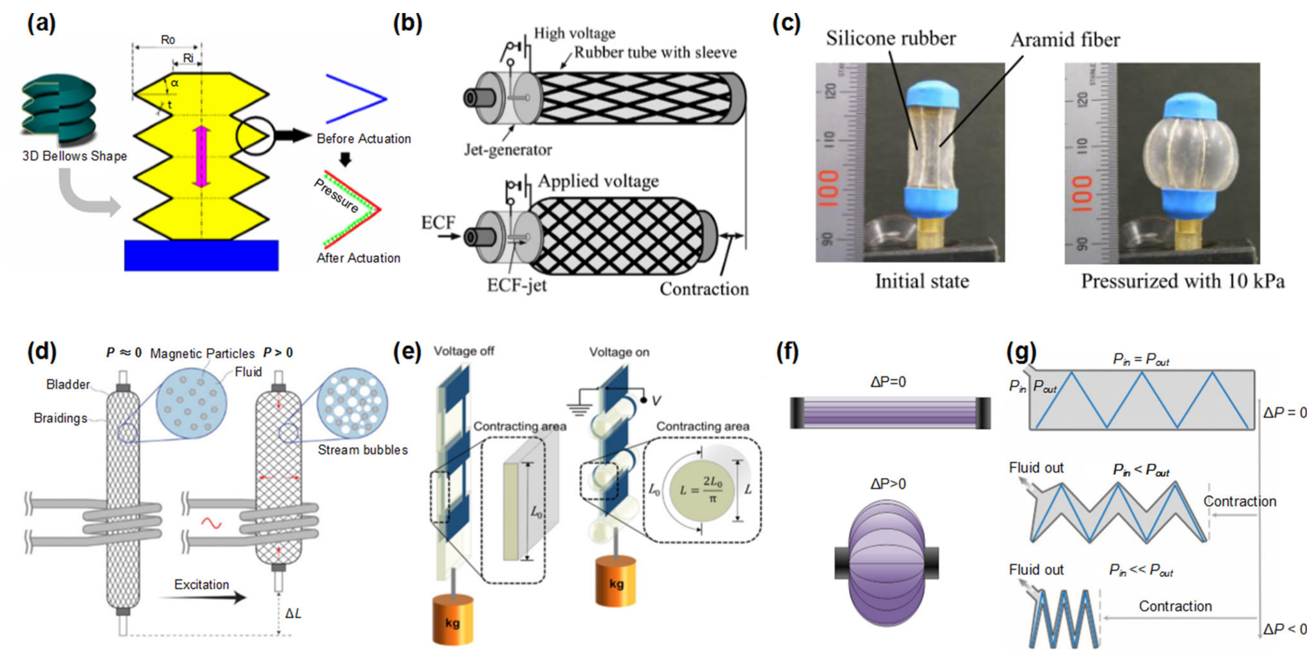

Fig. 3 **a** The schematic of a bellow-type FAM which could generate linear motion when the angle of the folds in bellow is changed. Reproduced with permission from [47]. Copyright 2006, Elsevier. **b** a McKibben-type artificial muscle could produce contraction motion based on ECF-jet. Reproduced with permission from [49]. Copyright 2010, Taylor & Francis Group. **c** a clamping unit of an in-pipe mobile robot could provide linear motion, whose tube is reinforced with fibers along its axis. Reproduced with permission from [50]. Copyright 2011, The Japan Society of Mechanical Engineers. **d** an untethered McKibben-type artificial muscle that can generate an axial contractile strain and radial expansion through liquid-to-gas phase transitions under magnetic field. Reproduced with permission from [51]. Copyright 2020, American Association for the Advancement of Science. **e** a Peano-type actuator uses both electrostatic and hydraulic principles to linearly contract on application of a voltage in a muscle-like fashion. Reproduced with permission from [54]. Copyright 2018, American Association for the Advancement of Science. **f** the schematic of pleated muscle that could contract or recover; **g** a kind of fluid-driven origami-inspired artificial muscles, in which the muscle system consists of a compressible solid skeletal structure, a flexible fluid-tight skin, and a fluid medium. Reproduced under the terms of the CC BY-NC-ND license [41]. Copyright 2017. The Authors, published by PNAS

ing different chambers of the FAMs; (2) asymmetric structure designs of FAMs; and (3) utilization of different materials in FAMs.

First of all, many FAMs with uniformly distributed chambers have been demonstrated, which can bend in multiple directions by selectively pressurizing different chambers. This type of bending FAM was firstly presented by Suzumori et al. in 1992, which was suitable for robotic systems, including fingers, arms, or legs, as shown in Fig. 4a [61]. Subsequently, a number of FAMs that can generate polydirectional bending motions have been reported with the same strategy. For instance, Takemura et al. have developed a set of fingers [62–67] using ECF, and all fingers consist of a power source and a tube with two chambers. This design allows the antagonistic action by expanding one chamber and naturally shrinking the other chamber, thereby generating the bending deformation. Furthermore, the two-DOF bending motion powered by ECF fluid can be achieved by placing three chambers along its axis, as shown in Fig. 4b [68]. Besides, the electrorheological (ER) fluids are also used to build this type of bending FAMs. Miyoshi et al. demonstrated an ER bending FAM with two chambers, which can generate bidirectional bending deformation through controlling two ER microvalves [69]. Interestingly, the outflow period and inflow period were described in such a FAM. Specifically, in the outflow period, the FAM bent downward when a voltage was applied to the lower microvalve. In the successive inflow period, the voltage was applied to the upper microvalve and the ER fluids sucked by the pressure transmitter flows out from the lower chamber at the same time, thereby the FAM bent downward further. Although this promising FAM possesses the advantages in power density, energy-saving, and miniaturization, they are still at the stage of laboratory research and additional power sources are also needed in operation. Notably, liquid-to-gas transitions have also been used in bending FAMs. Han et al. proposed a self-contained, untethered, and programmable soft FAM with three chambers based on liquid–vapor phase transition, which can produce bending motions, as shown in Fig. 4c [70]. Interestingly, this FAM is inspired by the stem bending of sunflowers due to the volume changes induced by the asymmetric multiplication of cells.

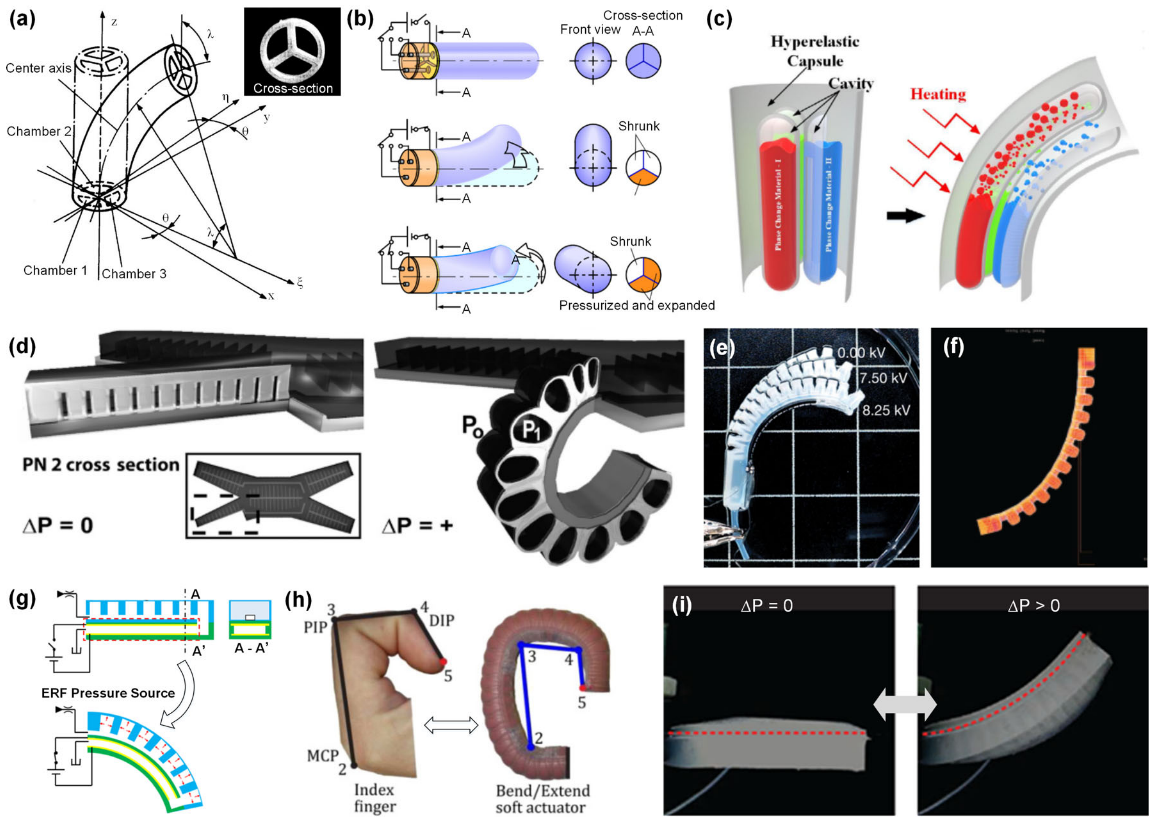

Fig. 4 **a** A kind of bending FAM with three uniformly distributed chambers. Reproduced with permission from [61]. Copyright 1992, IEEE. **b** a robotic finger with three chambers could generate 2-DOF bending deformation based on ECF. Reproduced with permission from [68]. Copyright 2006, Elsevier. **c** an untethered and programmable soft FAM with three chambers, which can produce bending motions based on liquid–vapor phase transition. Reproduced under the terms of the CC BY license [70]. Copyright 2019. The Authors, published by John Wiley & Sons. **d** a kind of soft robot with PneuNets that had asymmetrical channels, in which these channels could be curved when air source is supplied. Reproduced with permission from [71]. Copyright 2011, National Academy of Sciences. **e** a bending FAM with asymmetrical channels could generate bending deformation, in which the FAM was integrated with a stretchable pump based on EHD. Reproduced with permission from [73]. Copyright 2019, Springer Nature. **f** a cantilever FAM with asymmetric corrugated shape could produce bending motion. Reproduced with permission from [75]. Copyright 2009, IEEE. **g** a fluidic elastomer FAM could generate bending motion based on ERF. Reproduced with permission from [74]. Copyright 2020, Springer Nature. **h** a soft FAM with segmented fiber reinforcement configurations could generate multiple forms of motion to imitate the bending of fingers. Reproduced with permission from [77]. Copyright 2015, Elsevier. **i** an elastomer bending FAM with constraint layer could produce bending motion when air source is supplied. Reproduced with permission from [78]. Copyright 2012, IEEE

Different from the strategy of selectively pressurizing different chambers, the asymmetric structure designs of FAMs can also achieve bending deformation under the same fluidic pressure based on the different deformation capability of asymmetric structures in different parts of the FAMs. This method has been demonstrated in many works with different working fluids. For instance, Shepherd et al. presented a soft robot with PneuNets that had asymmetrical channels embedded in FAMs, and these chambers can be curved under the action of pressurized fluid, as shown in Fig. 4d [71]. Zhang et al. introduced a similar FAM that was made of dielectric elastomer (DE) and hydrogel, in which the inflated DE balloon could act as a hydraulic source to actuate the hydrogel chambers, and the pressure of the containing water could be tuned by the applied voltage [72]. Besides, Cacucciolo et al. presented a bending FAM with similar structures, in which the FAM was integrated with a stretchable pump based on EHD, as shown in Fig. 4e [73]. This bending strategy can also be realized via ER fluids. A notable example is that Sudhawiyangkul et al. described a soft microactuator with two unsymmetrical chambers that can produce bending deformation based on ER fluid, as shown in Fig. 4g [74]. The principle of this soft FAM is that the apparent viscosity is increased when voltage is applied to the microvalve to cause the poor liquidity of ECF in the microvalve, and ER flows into the extensible upper chamber, which will lead the FAM to bend downward. In addition to the asymmetric channels, Wakimoto et al. reported a cantilever FAM that added a three-dimensional corrugated shape to a portion of the cantilever, thereby causing asymmetric structures, and the bending motion could be further modified and amplified, as shown in Fig. 4f [75]. Besides, Deimel described a fiber-reinforced FAM with asymmetrical architecture, which consisted of a semi-cylindrical elastomer bladder wrapped with inextensible reinforcements [76]. Furthermore, Polygerinos et al. demonstrated a soft FAM with segmented fiber reinforcement configurations, in which the FAM can generate multiple forms of motion to imitate the bending of fingers, as shown in Fig. 4h [77].

Alternatively, FAMs made from different stiffness materials will also be widely used to produce bending actuation under the same fluidic pressure. In this type of FAM, the stiffness of the side with a filler or constraint layer is larger than that of another side without a filler or constraint layer, leading to their curving deformation. For instance, D. Onal et al. presented a fluidic elastomer bending FAM with a large actuation range, as shown in Fig. 4i [78]. When the pressurized fluids are supplied, the embedded channels expand laterally and bend the composite due to an inextensible thin sheet on the top layer.

Torsional FAM

Many biological muscles like the elephant trunk, the mammalian tongue, and octopus arms, etc., exploit the abilities to generate the complicated deformation that coupled with the torsional motion. A notable example is that the helical/oblique muscle fibers enable the elephant trunk to generate the torsional motion. Inspired by this, a FAM capable of torsional deformation has been developed to mimic the elephant trunk by Guan et al. [79]. Compared with linear and bending FAMs, the higher requirement is imposed on the design concerning torsional FAMs. So far, a few torsional FAMs have been reported, and these existing torsional FAMs could be roughly categorized into the following three groups: (1) fibers or tubes are wound in a helical pattern around the cylindrical FAMs; (2) several chambers or voids are placed into the FAMs in a well-laid-out way; (3) some innovative designs of architectures, such as origami structure, are applied in the FAMs.

So far, several torsional FAMs have been developed based on the strategy that fibers or tubes wound in a helical pattern around the cylindrical FAMs. For instance, Schaffner et al. introduced a PAM inspired by the elephant trunk, which comprised an elastomeric body whose surface was decorated with helical reinforcing stripes, as shown in Fig. 5a [80]. Connolly et al. developed a similar FAM with fibers helically surrounded outside, which can generate similar torsional motions, as shown in figure [81]. Besides, Sanan et al. presented a torsional FAM (figure), of which the tubes are arranged helically to form the main cylinder of the FAM, thereby obtaining the rotation angle of about 40 degrees [52]. Notably, a motion that combines twisting and extension was obtained by embedding a helical strip of paper into an elastomer tube, as shown in Fig. 5b. Besides, in this work, a range of motions including extension, contraction, twisting, bending, and combination of these, has been demonstrated by using composites of paper and a highly elastomeric siloxane [82].

Alternatively, torsional FAMs can also be constructed by placing several chambers or voids into the elastomeric FAMs in a well-laid-out way. Yang et al. proposed an elastic framework integrated with several cylindrical air chambers, as shown in Fig. 5c, which could approximately yield a maximum rotation angle of about 30° [83]. Besides, Gorissena et al. presented a flexible FAM that is capable of delivering a large torsional motion (6.5 degrees/mm at a pressure of 178 kPa) upon pressurization by producing several pressurizable voids based on back-to-back bonding of angled arrays, as shown in Fig. 5d [84].

Innovative architectures of FAMs could also be used to achieve the torsional deformation. Some works have been done to prove the feasibility of this strategy. Jiao et al. took inspiration from the origami structure to build a set of novel torsional FAMs, as shown in Fig. 5e [85]. The torsional deformation of these origami-inspired FAMs is accompanied by other motions (i.e., contraction and bending). Interestingly, the single torsional motion was achieved by the combinations of two FAMs. Meanwhile, Lee et al. presented a novel torsional unit, which could also produce torsional motion when the pressurized air was applied, as shown in Fig. 5f. Unfortunately, this type of torsional unit displayed poor performance (torsional angle is only about 3° at 50 kPa of air pressure) [86]. Achieving large torsional deformation is still a challenge for the design of FAMs. Besides, most of the existing schemes for torsional motion cannot avoid the coupling of other motions, for instance, torsional deformation is frequently accompanied by elongation or contraction.

In summary, there are many admirable design strategies that endow the FAMs with abilities of contract, elongate, bend, or twist, and most of these schemes are created with reference of natural communities in view of extraordinary versatility and multifunctionality of natural organisms. Although some achievements have been made, there still remains considerable work to be done before reliable, durable, controllable, and untethered FAMs that can match or even exceed biological muscles, can be designed and manufactured. To achieve this, the design of FAMs not only needs to implement the desired actuation but also requires tight integration of sensing and control. Meanwhile, the design of embedded components (e.g., sensors, circuitry, interface, etc.) should not significantly alter the flexibility and compliance of FAMs.

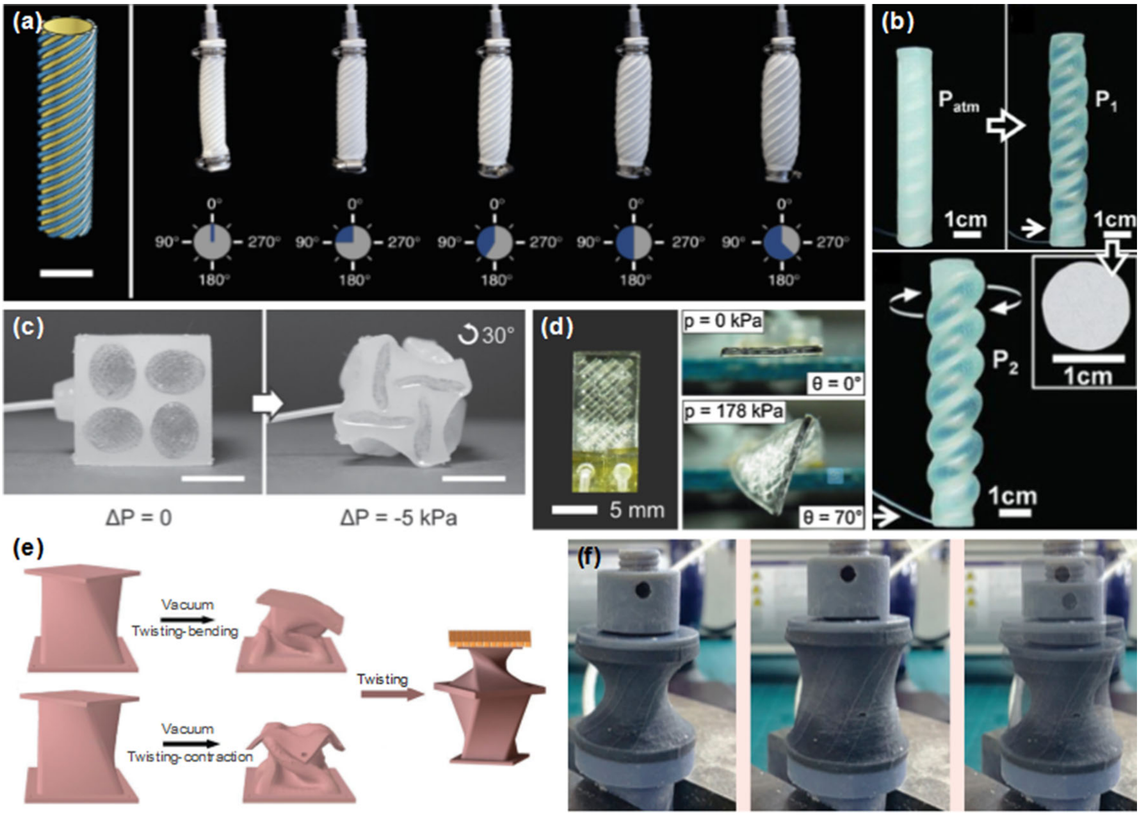

Fig. 5 **a** A PAM could produce torsional deformation, whose surface was decorated with helical reinforcing stripes. Reproduced under the terms of the CC BY license [80]. Copyright 2018. The Authors, published by Springer Nature. **b** a torsional FAM is built by a helical patterned paper strip wrapped around a cylindrical pneumatic channel. Reproduced with permission from [82]. Copyright 2012, John Wiley & Sons. **c** an elastic framework integrated with several cylindrical air chambers which could approximately yield a maximum rotation angle of about 30°. Reproduced with permission from [83]. Copyright 2015, John Wiley & Sons. **d** a flexible FAM with arranged voids could deliver a large torsional motion. Reproduced with permission from [84]. Copyright 2014, Elsevier. **e** a kind of FAM that takes the inspiration of origami could produce torsional motion and purely torsional motion could be achieved by the combinations of two units. Reproduced under the terms of the CC BY license [85]. Copyright 2019. The Authors, published by John Wiley & Sons. **f** a pneumatic unit with novel architecture could produce torsional motion when the pressurized air was applied. Reproduced with permission from [86]. Copyright 2014, IEEE

Manufacturing

So far, in-depth works have been done for the manufacture of FAMs with multifarious designs, and a variety of innovative fabrication methods have also been explored. These fabrication methods are tightly coupled with the choice of membrane materials and available equipment. For FAMs, the choice of membrane materials typically subjects to driving fluid, work environment, desired functionality, etc. Common materials used in FAMs are soft materials with Young's modulus in the order of 10^4–10^9 Pa that is in accordance with biological muscle tissue (Table 1 shows approximate Young's modulus for various materials). Similar to natural organisms, these soft materials tend to deform elastically in the face of loads and impacts, thereby showing good compliance. Specifically, typical materials used in FAMs include silicone elastomer, hydrogels, braided fabrics, polyurethane, etc. Note that many materials used in FAMs are viscoelastic, so hysteresis loss

Table 1 Approximate Young's modulus for various materials

Materials	Young's modulus
Biological tissue	
Tooth enamel	83 GPa
Bone, compact	18 GPa
Smooth muscle, contracted	0.01 MPa
Skin	0.42–0.85 MPa
Fat	0.5–1 kPa
Artificial materials	
Glass	50–90 GPa
Polyethylene (low density)	0.1–0.45 GPa
Polydimethylsiloxane	0.5–5 MPa
Silicone rubber	1–50 MPa
Hydrogel	1–100 kPa

Data are combined from [87–89]

is another important factor in material selection, that is, pure elastic materials do not dissipate energy during loading and unloading, but viscoelastic materials will lead to energy loss. As less viscous elastomers, silicone is the most commonly used material for FAMs that involve high cycle loading or require high elastic resilience, in which they can also exhibit tremendous and continuous deformation without the leakage of gas or liquid under the pneumatic or hydraulic actuation. Besides, hydrogels are also a kind of attractive material in FAMs due to their easy manufacturing processes, biocompatible, and low elastic modulus. Correspondingly, a number of prototyping techniques have been explored to manufacture FAMs with various structures. As mentioned before, these manufacturing methods are tightly coupled with material selections.

As follows, we will discuss several common methods for the manufacture of FAMs, including conventional fabrication methods (such as molding and casting, soft lithography, shape deposition manufacturing (SDM)) and the three-dimensional (3D) printing.

Conventional fabrication methods

One of the most commonly used fabrication methods for FAMs is the casting or molding, in which the rigid molds are used to cast silicone- or elastomer-based structures, as shown in Fig. 6a. For all FAMs, the fluidic chambers or pathways are generally included within their body, and casting and molding technologies allow the easy integration of these chambers in the FAMs [75, 77, 83, 90–94]. This fabrication method takes advantage of low cost, simplicity, and relatively quickly. However, it could not manufacture sophisticated FAMs with complex internal architectures because the geometry of the components is limited to the mold structure. Although this drawback could be partially solved by splitting the complex FAMs into many simpler modules, it would spend much labor and more time in operating and also difficult for small-scale FAMs. Additionally, some undesired defects such as bubbles could also be produced in the elastomer body during casting and molding processes.

Soft lithography is a technique that is always used to create microdevices or 3D structures with internal channels using molding and embossing an elastomer on a mold, as shown in Fig. 6b. This technique permits the inclusion of channels and the addition of materials such as fiber, paper, or plastic fields into FAMs. Many FAMs have been fabricated by using this method, in which microchannels could be obtained [71, 84, 95, 96]. Although this method is widely used to fabricate FAMs, in the multistep lamination process of soft lithography there are obvious bonding seams that are not firm and easily tore under the high pressure. Besides, the layering process used in this method limits the ability to produce truly 3D structures and also time-consuming.

SDM is a solid freeform fabrication process that systematically combines material deposition with material removal processes, as shown in Fig. 6c. SDM technology was first used to fabricate the force-sensing robotic fingers [97]. The main advantage of this fabrication method is that it can combine rigid and flexible materials and embed sensors, circuits, and other parts into the FAMs. Based on this feature, SDM technology has been used in the manufacture of FAMs [98, 99]. However, some shortcomings of SDM still need to be solved. Typically, it is hard for SDM to obtain an ideal surface with smooth contour owing to the utilization of soft supporting materials. Meanwhile, SDM is a relatively complicated fabrication process with a high cost and the processing environment has higher requirements during the deposition process.

Three-dimensional (3D) printing

In contrast to conventional fabrication methods, three-dimensional (3D) printing is an advanced manufacturing technology that digitally creates physical 3D objects by successive addition of materials. Since the first stereolithography manufacturing system appears in the 1980s, 3D printing has been widely used in various fields after years of development [101, 102]. Compared with the aforementioned 2D or 2.5D fabrication methods with many processing procedures, 3D printing can directly fabricate FAMs with very intricate and complex geometries. Early 3D printing technologies were limited to rigid materials and were typically used to fabricate hard molds of FAMs. Then, the commercial rubber was poured into these rigid printed molds and left to cure into shape. This fabrication method that casts soft FAMs by using 3D printed rigid molds, is by far one of the most common approaches for manufacturing FAMs, [77, 83, 92, 93] owing to its low-cost, simple process, expendable, and relatively rapid fabrication. In the last few years, 3D printing has increasingly been a technology that was directly used to fabricate FAMs with complex structures [103, 104]. So far, different kinds of 3D printing technologies have been employed to construct FAMs with various architectures, including fused deposition modeling (FDM), direct ink writing (DIW), selective laser sintering (SLS), stereolithography (SLA).

Fused deposition modeling. FDM is a popular and affordable 3D printing technology, which lays out the materials in layers through the melting of the printing filament supplied to the FDM printer, as shown in Fig. 7a. With the advent of different filament sources (e.g., thermoplastic elastomer filament) for the soft machines, the FDM method has been widely used to fabricate FAMs with complex structures. For instance, Yap et al. presented a novel technique for direct 3D printing of soft FAMs using 3D printers based on FDM technology [105]. Besides, Miriyev et al. printed silicone–ethanol

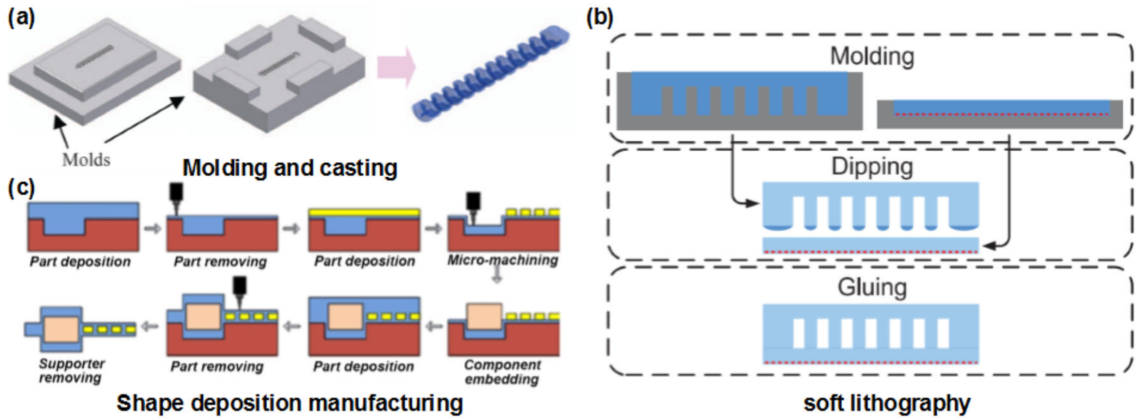

Fig. 6 Common conventional fabrication methods for FAMs, including **a** molding and casting, Reproduced with permission from [75]. Copyright 2009, IEEE. **b** soft lithography, Reproduced with permission from [78]. Copyright 2012, IEEE. and c shape deposition manufacturing. Reproduced with permission from [100]. Copyright 2009, Springer Nature

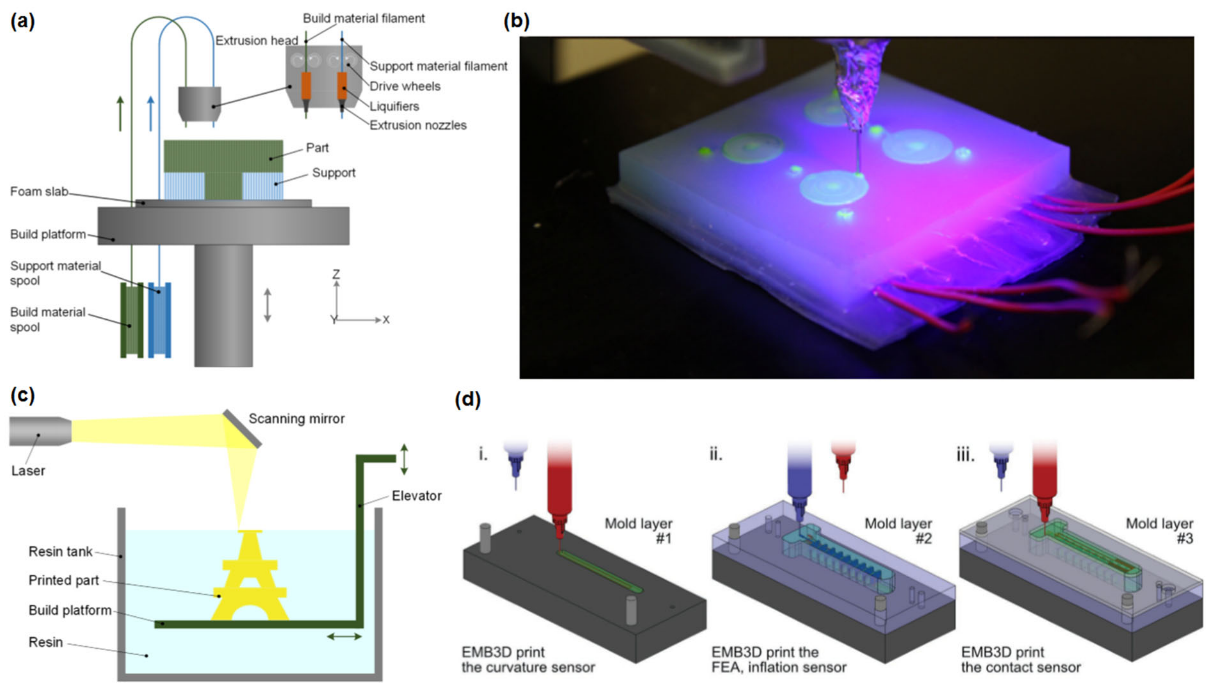

Fig. 7 Different 3D printing methods used in FAMs, including **a** fused deposition modeling; **b** direct ink writing; Reproduced with permission from [110]. Copyright 2015, Elsevier. **c** stereolithography; and **d** multi-material 3D printing. Reproduced with permission from [117]. Copyright 2018, John Wiley & Sons

emulsions by using commercial FDM machines to create a soft FAM that can expand up to 900% via liquid–vapor transition [106]. In general, this 3D printing technology takes advantage of its accessibility, easy maintenance, and abundantly consumable materials. However, it could introduce defects or voids into FAMs because the resolution of FDM is restricted by the nozzle diameter. Thus, it is highlighted that the wall thickness of FAMs should be three times the nozzle size at least [105]. Additionally, this fabrication method always requires a supporting material due to the parts made of soft materials that tend to deform under its weight during the printing process [107]. Another limitation of FDM is material compatibility, that is, only thermoplastic polymers (e.g., acrylonitrile butadiene styrene, polylactic acid, etc.) can be used in this technology due to the heating and cooling process, and liquid forms such as room temperature vulcanizing (RTV) silicones and gels cannot be used in FDM process [108].

Direct ink writing. DIW is also used for 3D manufacturing FAMs, in which the liquid-phase "ink" is dispensed out of small nozzles under controlled flow rates and deposited along digitally defined paths to fabricate 3D structures layer-by-layer. The concept of this technique is very close to FDM except for the difference that the DIW process depends on the feedstock rheology behavior to maintain the shape of the printed part in the time [109]. DIW is widely used for printing hydrogel and silicone [108], and several FAMs have been manufactured using this technique. For instance, Robinson et al. reported FAMs integrated with highly extensible sensing skin that was fabricated by the DIW technique, as shown in Fig. 7b [110]. Generally, DIW is a simple, flexible, and inexpensive method, which is suitable for many kinds of materials, including ceramics, metal alloys, polymers, and even edible materials, etc. [111]. Nevertheless, DIW has the limitation that it is not possible for it to obtain highly dense pieces, thereby limiting their application.

Selective laser sintering. SLS is an alternative 3D fabrication approach for FAMs. During SLS, tiny particles of plastic, ceramic, or glass are fused by heat from a high-power laser to form a 3D object. Rost et al. used a combination of reinforcement learning and SLS to manufacture a multi-finger soft robotic handmade of FAMs that was capable of executing gripping, lifting, and rotating tasks [112]. Scharff et al. [113] conducted a case study that multiple FAMs, sensors, and structural components were integrated into a soft robotic hand using mono-material SLS. As for this 3D printing technology, there is no need for supporting material and the FAMs fabricated by this method normally have relatively high strength. However, the objects manufactured by SLS have a relatively rough surface and a complicated postprocessing process always is needed.

Stereolithography. SLA is also a type of 3D printing technology that is used for manufacturing FAMs, in which a computer-controlled moving laser beam is utilized to build up the required structure in a layer-by-layer fashion, from a liquid polymer that hardens on contact with laser light, as shown in Fig. 7c. In the synthesis process, the buoyant forces provided by the dense medium allow this technique to construct objects with thin or overhanging structures [104]. Peele et al. employed the digital mask projection stereolithography to manufacture multi-degree of freedom soft FAMs with complex internal architectures [114]. Patel et al. reported a kind of soft FAM that exhibited large bending deformation under pressurized air along with FEA simulations, which was manufactured by the digital light processing (a sort of SLA technology) [115]. Typically, this technique could maintain a high resolution and rapidly manufacture numerous parts in parallel. However, building entire objects with holographic patterning in a single step is unsuitable for large-scale manufacturing and the forming objects have relatively lower strength.

Multi-material 3D printing. Multi-material 3D printing has also widely been utilized in the manufacture of FAMs, which can deposit two or more types of materials simultaneously to build the respective FAMs. Many FAMs are fabricated by this relatively new form of 3D printing technology. For instance, Bartlett et al. fabricated a soft combustion-powered robot made of FAMs using multi-material 3D printing, and this robot was able to perform untethered jumping powered by the combustion of butane and oxygen [116]. Truby et al. reported a method for manufacturing soft FAMs innervated with a complex network of sensors via multi-material, as shown in Fig. 7d [117]. Drotman et al. reported a legged soft robot made of FAM that was capable of navigating unstructured terrain using multi-material 3D printing technology [118]. Han et al. built a bio-inspired hybrid finger with integrated ECF micropumps using multi-material 3D printing [119]. Wehner et al. reported a hybrid fabrication technology that integrates molding, soft lithography, and multi-material embedded 3D printing for manufacturing an entirely soft and autonomous robot inspired by the octopus [95]. The conventional single-material 3D printing, as opposed to multi-material 3D printing, is somewhat restrictive regarding the applications. With multi-material 3D printing, complex products and components with different materials can be manufactured rapidly.

Although 3D printing technology provides a promising approach for the manufacturing of FAMs, it remains difficult to build heterogeneous structures and integrate electronic or other functional components. Also, it has some inherent limitations of additive manufacturing, such as error propagation, limited materials. Additionally, another barrier for fabricating FAMs using different 3D printing technologies is the materials compatibility, for instance, only thermoplastic polymers can be used in the FDM process.

In summary, recent advances in soft materials offer a good basic condition for the advancement of FAMs. The comparison between different manufacturing technologies with respect to FAMs is shown in Table 2. Soft materials with different elastic modulus, viscoelastic properties, and mechanical functionalities have been explored to manufacture FAMs. To build advanced FAMs that are similar to biological organisms, there still require the progress in new multifunctional materials, for example, increasing the stretchability, developing self-healing materials, and endowing materials with sensing ability. Additionally, the fabrication methods for manufacturing rigid components or machines are not suitable for FAMs made from soft materials; thus, some innovative manufacturing approaches have been explored to solve the issue. Typical manufacturing methods have been discussed above, and a table that summarizes various kinds of fabrication methods for FAMs is given. Generally, the molding techniques give the designer a good control over material properties but require the construction of molds. Moreover, the 3D printing techniques provide possibilities to build FAMs with random morphology that could

Table 2 Summary of manufacturing technology with respect to FAMs

Manufacturing method	Material	Advantages	Disadvantages	References
Conventional fabrication methods				
Molding and casting	Elastic polymer	Rapid fabrication; simple process; low-cost	Unsuitable for complex architecture; have defects such as bubbles	[75, 77, 83, 90–94]
Soft lithography	Elastic polymer	Can fabricate channels with small size; repeatable process	Time-consuming; the forming objects have relatively low strength	[71, 84, 95, 96]
SDM	Soft and rigid materials	Can print both rigid and soft materials to fabricate an integrated part	Imperfect surfaces; Complicated fabrication process; High cost	[98, 99]
3D printing				
FDM	Thermoplastic polymer	Simple process; Highly adaptable;	Introduce heterogeneities, defects, or voids; Require a supporting material	[105, 106]
DIW	Liquid ink	Simple; flexible; Inexpensive	Hard to obtain highly dense pieces	[110]
SLS	Solid grain	No need for supporting materials; The forming objects have relatively high strength	Complicated postprocessing process; Relatively rough surface	[112, 113]
SLA	Liquid photosensitive resin	Can manufacture numerous parts in parallel; Maintain a high resolution	Unsuitable for large-scale manufacturing; The forming objects have relatively low strength	[114, 115]

not be fabricated otherwise. Nevertheless, one of the main limitations of 3D printing techniques is that the selection of material types is more restricted.

Sensing

Advanced sensors can enable FAMs to gain the ability of information sensing to lay a solid foundation for precise control. So far, a variety of sensing technologies have been developed for FAMs, which were used in robotics and biomedical applications. Toughly, these sensing methods can be categorized into three types: (1) traditional sensors, (2) flexible and complaint sensors, and (3) integrated smart materials.

Many traditional sensors, such as potentiometers [120, 121], inertial measurement units, encoders [88], cameras [96, 120, 122], are integrated into FAMs. These traditional sensors empower the systems with the capabilities of vision, internal monitoring, and external touch sensing. Besides, force feedback information could be obtained using pressure and strain sensors [123]. However, traditional sensors inevitably add the volume, stiffness, and additional structures to FAMs, which significantly limit the degrees of freedom (DOFs) of the FAMs that can be vital in certain applications such as medical and rehabilitation devices. Thus, scientists and engineers are devoted to developing flexible and stretchable sensors

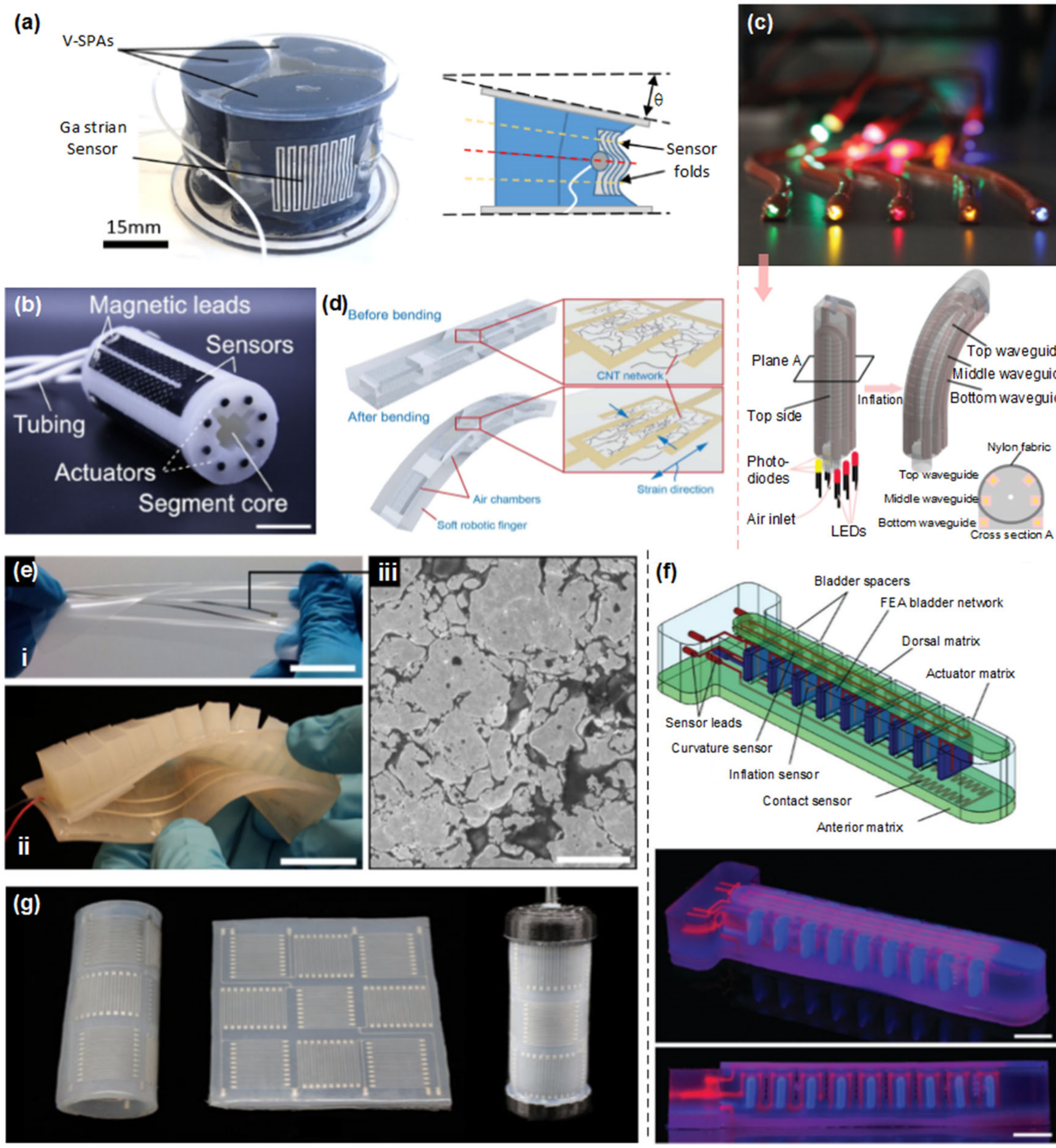

Fig. 8 **a** A soft strain sensor integrated with a vacuum-powered soft FAM enables sensing of its angular deformation upon activation. Reproduced with permission from [124]. Copyright 2019, IEEE. **b** Kirigami-inspired flexible sensor enables FAM to perceive their 3D configuration via deep learning Reproduced under the terms of the CC BY license [126]. Copyright 2020. The Authors, published by IEEE. **c** the stretchable optical waveguides (left image) are used in a prosthetic hand (right image) for strain sensing. Reproduced with permission from [130]. Copyright 2016, American Association for the Advancement of Science. **d** schematic illustration of soft robotic finger with integrated strain sensor that based on CNT network. Reproduced with permission from [131]. Copyright 2018, IEEE. **e** photograph (i and ii) and scanning electron micrograph (iii) of a soft sensor that embedded with silver conductors. Reproduced with permission from [132]. Copyright 2017, IEEE. **f** schematic illustrations (left) and images (right) of a soft somatosensitive FAM which contains multiple soft sensors such as conductive ionogel. Reproduced with permission from [117]. Copyright 2017, John Wiley & Sons. **g** a kind of soft skin contained the embedded microchannels that was filled with a room temperature liquid metal eutectic and is integrated into soft inflatable module. Reproduced with permission from [133]. Copyright 2018, IEEE.

that could be easily integrated into a flexible body without adding volume, stiffness, and additional structures. Recently, stretchable electronics are obtaining increasing attention. Typically, researchers tried to develop electronic circuits that could be printed on soft, stretchable, foldable, and even biocompatible materials. A notable example is the skin sensors used in vacuum-powered soft artificial muscles, as shown in Fig. 8a [124]. The conductive film sensor was also utilized for detecting the displacement of the FAMs [125]. Besides, a kind of Kirigami-inspired flexible sensor has been created for FAMs based on off-the-shelf sheets of electrically conductive silicone, as shown in Fig. 8b [126]. Among these flexible sensors, resistive and capacitive sensing methods are the most common forms, while the magnetic and optoelectronic sensors are also reported [127]. However, the majority of existing flexible sensors are not highly stretchable and their thin structures are vulnerable for repeated physical contacts [128].

An alternative sensing method is integrating the FAMs with sensors, such as low modulus elastomers combined with liquid-phase materials, which permits the FAMs to move with more freedom and dexterity. To date, a variety of conductive materials, including optical sensing, carbon nanotubes, hydrogels, liquid metals, ionic liquid, etc., have been integrated into microchannels of elastomeric FAMs for sensory feedback [129]. The deformation of microchannels will lead to a change in electrical resistance. For instance, Zhao et al. have reported the FAMs that integrate the stretchable optical waveguides, which was used for strain sensing of a soft hand, as shown in Fig. 8c [130]. Dang et al. have developed a pneumatic actuated soft robotic finger with an integrated stretchable strain sensor based on carbon nanotubes, as shown in Fig. 8d [131]. In addition to carbon nanotubes, other electrically conductive additives, such as carbon black, metal nanoparticles, and graphene, have also been integrated into elastomers to build the integration of actuation and sensing for FAMs. However, these rigid additives have an impact on the softness of FAMs, so there should be a balance between the desired conductivity and softness [8].

Except for the aforementioned solid substrates, the conductive liquids are also frequently applied in this sensing strategy. Koivikko et al. have shown that the conductive silver ink can serve as resistive curvature sensors for soft FAMs, as shown in figure, as shown in Fig. 8e [132]. Truby et al. [117] have printed the conductive ionogel and fugitive inks within three elastomeric matrices via embedded 3D printing, which enable the soft FAM to simultaneously obtain haptic, proprioceptive, and thermoceptive sensing, as shown in Fig. 8f. Kim et al. proposed a soft inflatable FAM module with self-contained sensing, as shown in Fig. 8g, in which the sensing skin of the module contained the embedded microchannels that were filled with a room-temperature liquid metal eutectic, i.e., gallium-indium (EGaIn) [133]. In general, EGaIn is the most commonly used metal liquid at room temperature that enclosed in soft structures to perceive the shape changes of FAMs owing to their relatively lower toxicity and reactivity compared with mercury. Because of the high-cost EGaIn, the aqueous sodium chloride (NaCl) is a commendably choice for conductive liquids. Helps et al. presented a proprioceptive flexible FAM using conductive working fluid, where the saltwater was initially used as the conductive liquid due to low cost, nontoxicity, and ready availability [134]. Generally, this integrated sensing method is advantageous over the other sensors that combine a standalone soft FAM and standalone sensor, because it significantly reduces the volume, mass, and complexity of the FAM. However, their drawbacks include (1) the potential risk of damage caused by leaking, and (2) the complicated manufacturing process, which would limit their widespread applications. Until now, advanced sensors have the properties of simple structures, compatible moduli, good stretchability, and low cost, etc., which are still needed for FAMs to extend their applications and improve their performance.

Despite the aforementioned achievements, FAMs sensing still at its infancy, there are many challenges to overcome toward perceptive artificial muscles. For controllable and self-aware systems, we need FAMs not only to sense their internal morphology but also can accurately tell external stimuli. To address these issues without sacrificing compliance intrinsic to natural organisms, innovations in multifunctional materials, robust multimodal sensors, stretchable conductors, fully integrated and/or wireless electronic interfaces, modeling, and data interpretation methods are highly demanded [128]. Meanwhile, the integration and compatibility of materials, that is, integrating soft actuation, sensing, and circuitry, imposes big challenges to manufacturing technology and interfacing.

Control

In contrast to rigid devices that can be described by six DOFs, the FAMs are made of soft materials that are elastic and could deform continuously with infinite DOFs. Such a feature makes it difficult to derive accurate and tractable dynamic models of FAMs. Consequently, the lack of accurate models leads to the difficult positions that the classical control methods can not directly be applied in the control of FAMs, which poses a great challenge to scientists and engineers. So far, many researches have been conducted to look for innovative solutions for the above issue, which are discussed in this section.

The kinematic and dynamic modeling is the basis of motion control and path planning of FAMs; thus, the modeling of FAMs is of vital importance. To date, the models to describe the characteristics of FAMs could be categorized into two groups: the theoretical model [135] and the phenomenological model [136–138]. The theoretical models were derived from the force generation, geometric structure, actuation pressure, contraction ratio, etc., of FAMs [139]. For instance, piecewise constant curvature (PCC) kinematics, as a largely simplified model, has been widely used in the control of the soft robotic community, which represents the soft robot as a finite collection of circular arcs [140]. Besides, several dynamics models also have been developed to employ control strategies for dynamic tasks and continuous interactions with the environment, including beam theory [141], Ritz–Galerkin models [142], and discrete Cosserat models [143]. Unfortunately, all these models oversimplify the deformation and ignore the viscoelasticity of soft materials within FAMs. In consequence, the accuracy and complexity of these models are unsatisfactory in practice. Additionally, a number of experimental methods have been conducted to obtain more accurate dynamics in view of extensive bio-inspirations in FAMs. Typical examples include the kinematics of horizontal and vertical caterpillar crawling [144], dynamic properties of caterpillar muscle [145], and analysis of the physiological characterization of the flexible arm of the octopus [146]. In order to predict the time-varying material profiles of FAMs, more accurate kinematics and dynamics models are still needed.

Based on these models, a number of methods to low-level control, inverse kinematics, dynamics operations, and planning of FAMs have been proposed. In general, the core issue of the control algorithm is that a sequence of inputs (i.e., pressure and fluid volume) should be found for FAMs to achieve the desired shape, position, and velocity [8]. In the open-loop control, the required quantities are given beforehand based on established models and the actuator is operated without obtaining feedback information from it. Farrow and Correll derived a constant curvature model for reliable bending control of cylindrical FAM [147]. Merola et al. combined a proportional-integral-derivative (PID) control scheme for FAM systems with a feedforward compensation to achieve fast and accurate tracking control performance [137]. However, open-loop control can hardly satisfy the demands in practice because of the oversimplified models or passively deformation in unstructured environments. In contrast, the closed-loop control has been demonstrated in several publications despite the lack of accurate and robust sensors. This control strategy provides a regulatory mechanism to reach the desired state through the real-time detecting information of FAMs. Katzschmann et al. proposed a FEM-based closed-loop control approach on a three-dimensional soft robotic arm made of FAMs, which has significant improvements over open-loop actuation when performing pose-to-pose control and trajectory tracking of a circle [93]. Marchese and Rus presented a closed-loop curvature control for a fluidic elastomer manipulator made of FAMs, which enables the manipulator to conform to arbitrary configurations in real time [148]. In some cases that FAMs have a slow sensory response, complex material dynamic, or high impedance within channels, the combinations of feedforward and feedback control are required for fast and accurate control. A typical example is that Turkseven et al. presented a control algorithm, which provided an accurate impedance control for FAMs with long transmission lines [149], have been reported. Except for the aforementioned model-based control methods, some researchers have also proposed model-free control algorithms that can realize the control of FAMs without any information about the characteristics of the FAM themselves. For instance, neural networks (NN) were used for the identification and control of nonlinear systems due to their universal approximation property [150]. Although some progress has been made in the control of FAMs by far, it is still at an infant stage and there still exist many issues to be dressed. It is difficult for FAMs to obtain accurate real-time model parameters of FAMs owing to their nonlinear time-varying characteristics. Besides, the FAMs also frequently suffer from uncertainties and external disturbances that lead to greater difficulty to control.

Application

Medical and rehabilitation

As mentioned above, the FAMs possess the advantages of high power outputs and inherent compliance, which can satisfy the safety and reliability of human–machine interaction devices. Moreover, FAMs have similar properties with those of human muscle, making it a promising option for medical devices, especially for rehabilitation treatment, as shown in Fig. 9. For instance, the fluid-driven exoskeleton can help disabled people to carry out rehabilitation training, such as assisting disabled people to stand up independently. The fluid-driven exoskeleton can also be used as a muscle-boosting device in the military field that improving the combat ability of individual soldiers. So far, many robotic devices for the rehabilitation treatment of upper and lower limb [151], ankle–foot [152–154], arm [155], hand [156], etc., have been reported based on PAMs. Compared with PAMs, HAMs with a fluidic medium may result in increased weight, but the unrivaled power density provided by HAMs enables them to assist the disabled people in rehabilitation (e.g., exoskeletons). Additionally, the use of different working fluid like water or oil could result in HAMs with different stiffnesses, which is specifically beneficial for exoskeleton design and control. For instance, a hydraulically actuated exo-musculature, consisting of a network of artificial hydro-muscles, has been reported and this FAM could be utilized as either perform-alone or wearable, human body-symbiotic robotic systems [157]. Besides, a hydraulic, portable, assistive, soft robotic glove has been developed, which is designed to augment hand rehabilitation for individuals with functional grasp pathologies [77].

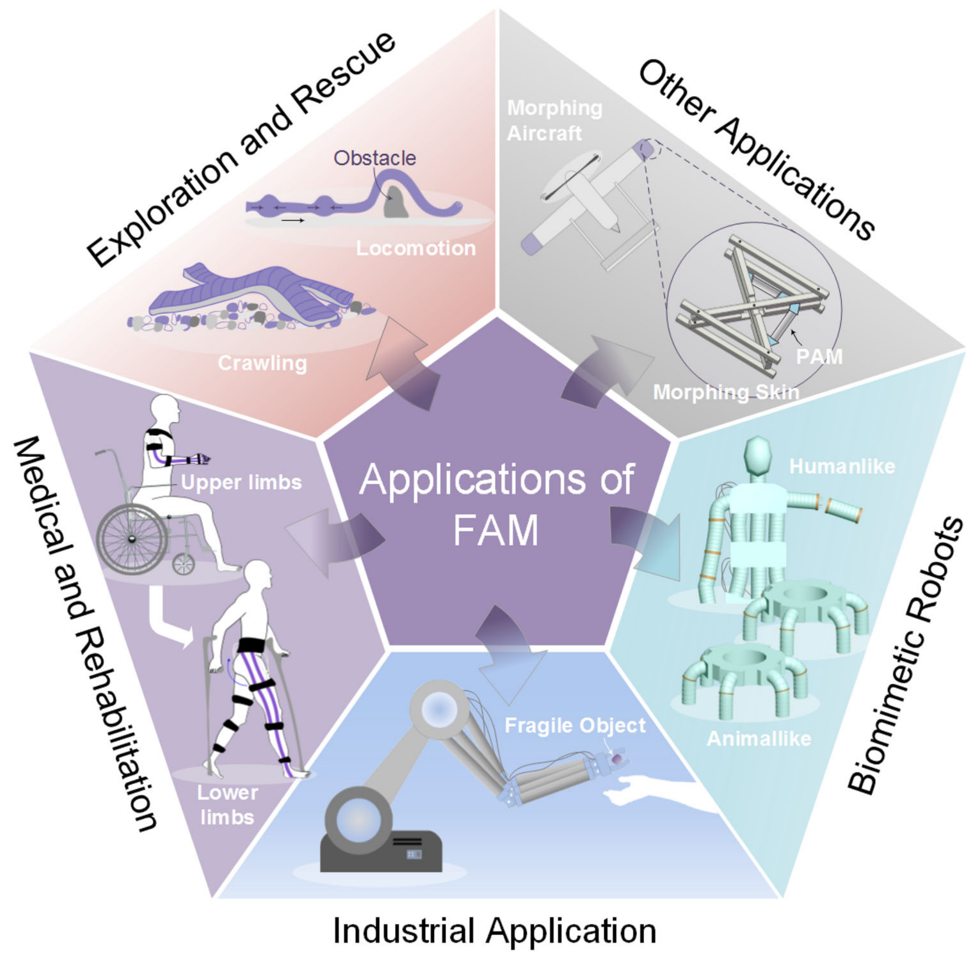

Fig. 9 Different application fields of FAMs, including medical and rehabilitation (e.g., exoskeletons for the rehabilitation of upper or lower limbs), industrial area (e.g., flexible gripper for grasping the fragile objects), biomimetic robots (e.g., humanlike or animal-like robots), exploration and rescue (e.g., soft robots made of FAMs can crawl on bumpy roads or avoid obstacles), and other applications (e.g., morphing skin on the wingtip of aircraft)

Industrial applications

The utilization of FAMs has received significant attention in the construction of industrial robots or devices in past decades. These FAMs are able to provide high torques at low and moderate speeds, and they also can be easily installed or disassembled because of their simple structures. Besides, the inherent compliance and shock resistance of FAMs can provide safer human–robot interaction. For instance, a number of robotic manipulators have been developed based on PAMs, which can assist in the handling of heavy loads [158], retrieval of radioactive materials [159, 160], or a simple positioning system [161]. Additionally, industrial grippers based on FAMs could change their shapes to cover the objects well according to the shapes and sizes of the target objects, so that they have a good advantage in the shape of irregular objects, especially fragile objects grasp [47, 58, 117, 162, 163].

Exploration and rescue

Soft robots or devices powered by pressurized fluid have recently attracted increasing attention in fields of exploration, search, and rescue. These soft robots made of FAMs have good damage resistance and could operate in confined spaces; thus, they can be well used in the areas of exploration and rescue. Meanwhile, these soft-bodied robots will not cause secondary damage for people who are under the rubble because of their compliant body. PAMs are suitable for actuating the portable machinery or robot in the terrestrial exploration or rescue due to their property of lightweight [164]. Notably, a class of simplified soft robots powered by pressurized air replace multiple control systems with one input, which can greatly reduce the number, weight, and complexity of the components needed to power the device in a variety of innovative applications in areas as diverse as space exploration, search, and rescue systems [165]. Besides, a set of novel PAMs inspired by root growth has been developed to fabricate the exploratory devices within the recent few years [166, 167]. Compared with PAMs, HAMs can offset the buoyancy underwater, possess the high force-weight ratio, and have high compatibility with the underwater environment; thus, HAMs have received increasing attention in marine exploration and rescue [122].

Bio-inspired robots

To date, FAMs have been widely applied in the field of robotics, especially soft robotics. On the one hand, the characteristics of FAMs are similar to those of actual biological muscles. Many researchers have committed to emulating the compliant and flexible structure of biological muscle, tendons, and skin. These biologically inspired robots made of FAMs can be categorized into two groups: robots that mimic the morphology of humans [168–170] and robots that imitate the physiology of animals [171, 172]. On the other hand, the FAMs are frequently used in the construction of soft-bodied robots that have full soft and complaint bodies. Generally, soft-bodied robots made of FAMs come in handy when facing unpredictable tasks and unstructured environments. So far, in the soft robotic community, numerous bionic fluid-driven soft robots have been proposed, such as worm-like robots [81, 173, 174], snake-like robots, [91, 175]. Besides, hydraulic biomimetic robots have attracted extensive attention in underwater applications, where the surrounding water could be used as a reservoir. Furthermore, the bulky compressors of HAMs can be avoided underwater, making the compact design possible [122]. To date, a number of the biomimetic robotic fishes have been developed for the exploration and monitoring [59, 94, 176], which provide the advantage of soundlessly swimming undersea and implementing camouflage without disrupting fish schools.

Other applications

In addition to the aforementioned applications, FAMs can also be adopted in aerospace. For instance, an autonomously controlled deployable airdrop system, called "AGAS," has been presented, which was controlled via four PAMs [177]. Besides, a novel motion seat has been developed, which was designed for driving and flight simulator based on a hexapod structure with 6 spatially oriented PAMs [178]. Additionally, a novel morphing skin suitable as an aerodynamic surface has been proposed, which was designed to be actuated by a span-morphing pneumatic artificial muscle, as shown in Fig. 9 [179]. More applications should be explored in the future.

Summary and prospectives

This work takes a state-of-the-art review of existing researches on FAMs. The importance of incorporating biological inspirations into the design of FAMs is first introduced. Besides, various manufacturing technologies of FAMs, including conventional fabrication methods and 3D printing, are summarized. Existing researches on sensing and control of FAMs have also been discussed. The applications of FAMs into the medical and rehabilitation, industrial fields, exploration and rescue, and robots, etc. are presented.

Although great progress of the FAMs has been achieved in past decades, there still exist many challenges for developing high-performance FAMs that can replace the biological muscles. The capacities of the FAMs will directly determine the performances of robots or devices, and future FAMs should be self-contained, safe, portable, controllable, agile, powerful, and intelligent. First of all, the conventional FAMs need the external bulky and rigid compressors, or pumps to supply the pressurized fluids and the channels to transport fluids, which significantly increase the volume and weight of the systems of FAMs. Compared with the conventional FAMs, the portability of FAMs driven by smart fluids has been greatly improved. However, they also have some other problems, such as low safety, poor controllability, or narrow range of actuation force. Thus, the FAMs can strike a balance in the properties of high safety, considerable actuation, high controllability, rapid response speed, and good portability, etc., should be developed in future studies. Meanwhile, some special capabilities of biological muscles, such as the variable stiffness, self-healing, and information transmission, should be integrated into the FAMs in the future studies, enabling them to be powerful. New methods of energy harvesting, such as energy from nature or biological organisms, should be explored to make FAMs closer to biological muscles. In addition, lifetime is another concern of FAMs, and FAMs usually degrade fast with the increase of their working time. In contrast to FAMs, biological muscles have a very long cycle life, even for hundreds of years, because they contain regenerated cells. Therefore, advanced materials or methods are explored to produce durable FAMs with long life.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

Ethical approval This article does not contain any studies with human or animal subjects performed by any of the authors.

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