Soft Matter

REVIEW

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Soft Matter*, 2022, **18**, 7699

Recent advances in biomimetic soft robotics: fabrication approaches, driven strategies and applications

Xiaoxiao Dong,†[ab] Xiaohang Luo,†[c] Hong Zhao,*[a] Chenyu Qiao,[b] Jiapeng Li,[c] Jianhong Yi,[d] Li Yang, *[bd] Francisco J. Oropeza,[e] Travis Shihao Hu,[e] Quan Xu [c] and Hongbo Zeng *[b]

Compared to traditional rigid-bodied robots, soft robots are constructed using physically flexible/elastic bodies and electronics to mimic nature and enable novel applications in industry, healthcare, aviation, military, *etc.* Recently, the fabrication of robots on soft matter with great flexibility and compliance has enabled smooth and sophisticated 'multi-degree-of-freedom' 3D actuation to seamlessly interact with humans, other organisms and non-idealized environments in a highly complex and controllable manner. Herein, we summarize the fabrication approaches, driving strategies, novel applications, and future trends of soft robots. Firstly, we introduce the different fabrication approaches to prepare soft robots and compare and systematically discuss their advantages and disadvantages. Then, we present the actuator-based and material-based driving strategies of soft robotics and their characteristics. The representative applications of soft robotics in artificial intelligence, medicine, sensors, and engineering are summarized. Also, some remaining challenges and future perspectives in soft robotics are provided. This work highlights the recent advances of soft robotics in terms of functional material selection, structure design, control strategies and biomimicry, providing useful insights into the development of next-generation functional soft robotics.

Received 7th August 2022,
Accepted 17th September 2022

DOI: 10.1039/d2sm01067d

rsc.li/soft-matter-journal

1. Introduction

As semi-automatic or fully automatic intelligence machines, robots have some basic characteristics, for instance, cognitive and decision-making capabilities and programmable execution. They can assist or even replace humans in completing dangerous, heavy-duty, and complex tasks, improving the work efficiency and quality and expanding the scope of human activities and capabilities.[1–3] After decades of research, robotics has grown rapidly as an interdisciplinary field, where many robots have been developed for a wide range of applications in industry, healthcare, aviation, and military.[4–6] Traditional robots are usually designed based on rigid-body mechanics and mechanisms, which are much easier to control compared to 'systems or mechanisms' built by living organisms in nature. However, the performance of the mechanical structure, intelligence and stability of the control software, and the reliable design of circuitry have to be considered. In the case of rigid-bodied robotics, their simplification, flexibility and 3D actuation capability are substantially limited.[7–9] Specifically, they are usually expensive to fabricate and can only work in a predetermined environment. Routinely, due to the use of rigid metallic, plastic, and ceramic materials and rigid connecting links and relatively large volumes of rigid robots, their degree of freedom (DoF) is significantly limited, hindering their use in many situations.[10–12] It is expected that the preparation of soft robots with collaborative maneuverability and artificial intelligence capability will help overcome the above-mentioned issues and may become one of the future research trends.[13–15]

Soft robots, as a new generation of robotic production, have the ability to deform when actuated and allow smooth interactions with the environment. Soft robots are defined as systems capable of autonomous behavior, mainly composed of materials with an elastic modulus in the range of soft biological materials.[16]

[a] *College of Mechanical and Transportation Engineering, China University of Petroleum-Beijing, Beijing 102249, China. E-mail: hzhao_cn@163.com*
[b] *Department of Chemical and Materials Engineering, University of Alberta, Edmonton T6G 1H9, Canada. E-mail: yanglikmust@163.com, hongbo.zeng@ualberta.ca*
[c] *State Key Laboratory of Heavy Oil Processing, China University of Petroleum-Beijing, Beijing 102249, China*
[d] *Faculty of Metallurgical and Energy Engineering, Kunming University of Science and Technology, Kunming 650093, China. E-mail: yanglikmust@163.com*
[e] *Department of Mechanical Engineering, California State University, Los Angeles, California 90032, USA*

† These authors contributed equally to this work.

Compared with conventional hard robots, soft robots complete difficult 3D actuation with low mechanical impedance and relatively high compliance in a safe state. In addition, the performance of soft robots can be designed to enable them to pick up objects hundreds of times their weight with excellent characteristics.[17–20] For the design and preparation of soft robots, the available materials and manufactured structures are two important aspects. In addition, bioinspiration plays an important role in the preparation of soft robots. Bio-inspired systems usually consider the morphology, characteristics, and motion states of organisms. Researchers have taken inspiration from many organisms to successfully prepare soft robots with functional characteristics, such as chameleons,[21] worms,[22–24] fishes,[25–27] snakes,[28] octopuses,[29,30] and frogs.[31] Initially, flexible elastomer materials were used to prepare soft robots, such as polymers and silicone rubber.[18,32] However, with the advancement of research, to make soft robots more intelligent, some smart materials such as stimuli-responsive materials (SRM), which can respond to stimuli from the environment (*e.g.*, temperature, light, electricity, and mechanical and chemical input[33–35]), have gradually appeared. In addition, shape-memory materials (including shape memory alloys (SMAs) and shape memory polymers (SMPs)) have application value in the field of soft robots due to their characteristics, where they can be restored to their initial state by exposure to external stimuli after deformation.[36] The fundamental reason for the deformation and recovery of SMAs is that they transform from a crystalline structure to another phase and release the stored elastic energy under temperature changes.[29,37] SMPs have similar characteristics, but they exhibit a lower density, stiffness, and energy release during their transition.[38] Regarding the manufacturing of structures, to create compliant mechanisms, some soft robots are still rigid-linked systems[39–41] and their designs are primarily rigid-body architectures associated with soft components.[13,42,43] An inflatable structure is one of the simplest structures in soft robots made entirely of flexible materials.[44,45] In addition, inspiration from the origami and kirigami techniques has led to the design of special structures that can have flexible motion around a specific axis, whereas have high off-axis stiffness when exposed to mechanical over-constraints.[28,46–48] With the development of technology, soft robots are innovatively designed and manufactured rather than artificially assembled by elementary blocks. However, the preparation of soft robots still faces challenges and opportunities and a real technological breakthrough is still imminent.[49–52]

The research and development of soft robots first need to consider their functions and application scenarios, and then realize their fabrication by designing structures and selecting appropriate materials. To improve the preparation efficiency, it is necessary to combine some appropriate preparation methods. Some reviews about soft robots have been published in recent years, including their design and fabrication process,[3,16,53,54] selected materials,[55–59] manufacturing methods,[60–63] actuation technologies,[64] and application opportunities.[65] However, a comprehensive overview of the field of soft robotics is necessary and significant for readers to quickly understand this field.

In the current review, we provide a comprehensive overview of the representative studies and recent advances in soft robotics, including the popular preparation approaches (Section 2), driving strategies (actuator and materials based) (Section 3), and emerging applications (*i.e.*, artificial intelligence, medical, sensors, and others) (Section 4) of soft robots. Finally, the challenges and perspectives of soft robotics are discussed.

2. The fabrication approaches of soft robots

The preparation of soft robots is closely related to the choice of materials and structures, and the fabrication approaches are particularly important.[60] In this section, we classify the fabrication approaches of soft robots into three types, as follows: (i) top-down approaches (*i.e.*, template-assisted casting method, laser, and soft lithography to define polymer objects), (ii) bottom-up approaches (*i.e.*, adding reinforcement and additive manufacturing solutions), and (iii) a combination of the top-down and bottom-up approaches, where several subparts of soft robots are prepared in various ways and their overall fabrication requires a combination of the above-mentioned approaches. In addition, the fabrication and synthesis of some important components of soft robots will be presented.

2.1 Molding

Molding is a relatively low-cost and convenient fabrication method, which involves creating something by casting it in a mold and is relatively suitable for the preparation of large-size (such as centimeter, decimeter, and meter level) materials and structures with chambers for soft robot. Molding was employed for a wide range of applications in early biomimetic soft robots (*e.g.*, fishes,[25] earthworms,[66] and cephalopod molluscs[67]). However, in the soft robots fabricated using the molding method, they may have air bubbles mixed in their materials during their preparation, which may weaken the final structures of soft robots, further affecting their quality. Accordingly, vacuum degassing the mixture, spinning the mold, shaking the molding and applying centrifugal force can effectively eliminate the bubbles generated during the fabrication and synthesis of soft robots.[68–70] Manufacturing complex internal structures, volumes and undercuts is also a difficult problem to solve. The emerging lost-wax casting can enable the formation of arbitrarily shaped internal channels, thus solving the above-mentioned problems to a certain extent.[71–73]

The method of the molding continues to be subdivided into multiple categories, such as rotational molding, multi-step molding, vacuum casting, infusion molding, and injection molding. Different molding modes are employed for different types of materials, also possessing the corresponding functions, such as infusion molding, which is usually used to fabricate fiber-reinforced composites and can also be adapted to soft composites with a fibrous matrix.[69] In terms of injection molding, due to the high cost of the machine, requirement of large volumes of liquid silicone, and difficulty to change the materials quickly between injections, this technology was not popular for the preparation of soft robots until Bell *et al.* developed a low-cost injection molding system and process recently. They introduced some applications that can only be achieved by injection molding due to geometry, embedded components, and cure times.[60,74–76] Some representative examples of other different types of molding methods are presented below.

Rotational molding is a method with the obvious advantage of simplifying the soft machine fabrication process. Shepherd and co-workers used the rotational casting method to fabricate monolithic soft machines using thermosetting elastomers in one step for the first time, and the casted soft actuator generated a large force (>25 N) at its tip, which is nearly a ten-fold increase compared to similar reported devices.[77] In addition, they prepared a wearable assistance device, where users can apply force at their fingertips using the rotational molding fabrication approach, and the rotational casting machine with multiple molds is shown in Fig. 1a. The prepared rotational cast part consisted of a series of separate units connected by a common flat layer. A steel wire was passed through each chamber and encapsulated with the same elastomer to ensure that compressed air could be applied to each unit. The prepared cuboid actuator achieved a good bending effect at 40 kPa (in Fig. 1b). Based on this cuboid actuator, they prepared a system that uses electromyography (EMG) sensors and micro-controllers to open and close solenoid valves based on compressed air to power finger actuators.[78] In addition, rotational molding, as a fast and convenient way to prepare soft robots, played an important role in verifying the simulation results. Kriegman and co-workers prepared voxels using a single-axis rotational molding machine, which poured silicone into an acrylic mold (Fig. 1c). Also, they used the prepared soft robots to simulate, manufacture and measure the simulation-reality gap of minimally complex but soft, locomoting machines. They proved that this fabrication method is more scalable than other robots that move from simulation to reality.[79]

Regarding the use of molding methods to fabricate soft robots, sometimes it is difficult to achieve the desired results in one step, and therefore the multi-step molding fabrication approach plays a key role. Germann *et al.* applied stretchable electro adhesion materials in soft robots. They used the molding method to inject an Ecoflex/CB mixture into a stainless-steel mold to form conductive traces, coated the traces with pure Ecoflex, and then de-molded the Ecoflex substrate with the bonded traces and spin-coated the conductive traces with an encapsulating layer of pure Ecoflex (Fig. 1d).[80] Based on analysis results, Wakimoto and co-workers fabricated a pneumatic rubber actuator with a 1.0 mm radius by a machining process for molds, vacuum rubber molding process and rubber bonding process with surface improvement by excimer light. The prepared actuator could realize large curling motion in two directions efficiently and quickly. This characteristic enabled the prepared materials to be successfully applied to the hand of a soft robot to achieve opening and closing motions with negative and positive pressure, respectively (Fig. 1e).[32]

The use of 3D printing technology has become a current trend in fabrication of molds for use in soft robotics. Onal and co-workers created molds using a fused deposition molding (FDM) 3D printing process on poly(acrylonitrile-*co*-butadiene-*co*-styrene) (ABS). They used a soft silicone rubber material (Smooth-on Ecoflex™ Supersoft 0030) to prepare two layers by molding and assembled the layers into an actuator by gluing (Fig. 1f). This is the general process used for the fabrication of soft fluidic elastomer robots.[81] Stark and co-workers also used 3D printing technology to fabricate injection molds using ABS material. A molding method using PDMS was applied to prepare a soft pump, which used gas combustion to actuate and corresponded to a high power density (up to 1000 watts per liter machine volume).[73] Similarly, Martinez *et al.* used ABS plastic-generated masters to mold the elastomers using a 3D printer. They used the printed mold to fabricate 3D tentacles (Fig. 1g). The process for the preparation of the 3D tentacles was simple, fast and relatively inexpensive, and also entirely compatible with the plastic modeling and extrusion techniques, making the fabricated soft robots light, compatible with high-speed drives and resistant to external damage.[82] The preparation methods in the above-mentioned works are simple, inexpensive and flexible in terms of operation, which provide a good design idea for similar research.

There are also some designs of bionic soft robots fabricated using 3D printed molds. Wang *et al.* used 3D printing to fabricate molds for the preparation of soft robots inspired by sea anemones. They successfully prepared a soft robot composed of soft sensing tentacles and magnetic stimulation shrinkable body using magnetic NdFeB/Ecoflex composites (Fig. 1h). This soft robot could detect the surrounding water flow velocity and guide the shrinkage/recovery through its bottom body.[83] Niu *et al.* used a similar method to fabricate a worm-like soft robot (Fig. 1i). This soft robot was driven by housing permanent magnetic patches in its soft body, which interacted with an external moving magnet-driven system. This is a low-cost strategy that can be applied in many fields.[84]

In addition, Kramer and co-workers used a 3D printed thermoplastic to produce molds and used the molds to fabricate a pneumatic soft robotic gripper. The modular design can foster the confidence of students and meet education objectives to a certain extent due to its simple operation characteristics.[85]

In summary, the molding method is a cost-efficient and facile process for the preparation of soft robots. However, it is difficult to manufacture internal volumes, undercuts, and complex internal structures, and the bubble-induced defects in the molding process need to be solved. As a basic method to fabricate soft robotics, molding is widely used in research and combined with other manufacturing technologies in some studies.

2.2 Etching, laser and soft lithography

Micro-robotics exhibit ideal performances, but due to their small size, they are usually more difficult to prepare. Etching, laser, and soft lithography methods are emerging for the easier fabrication and synthesis of relatively small-scale soft robots,

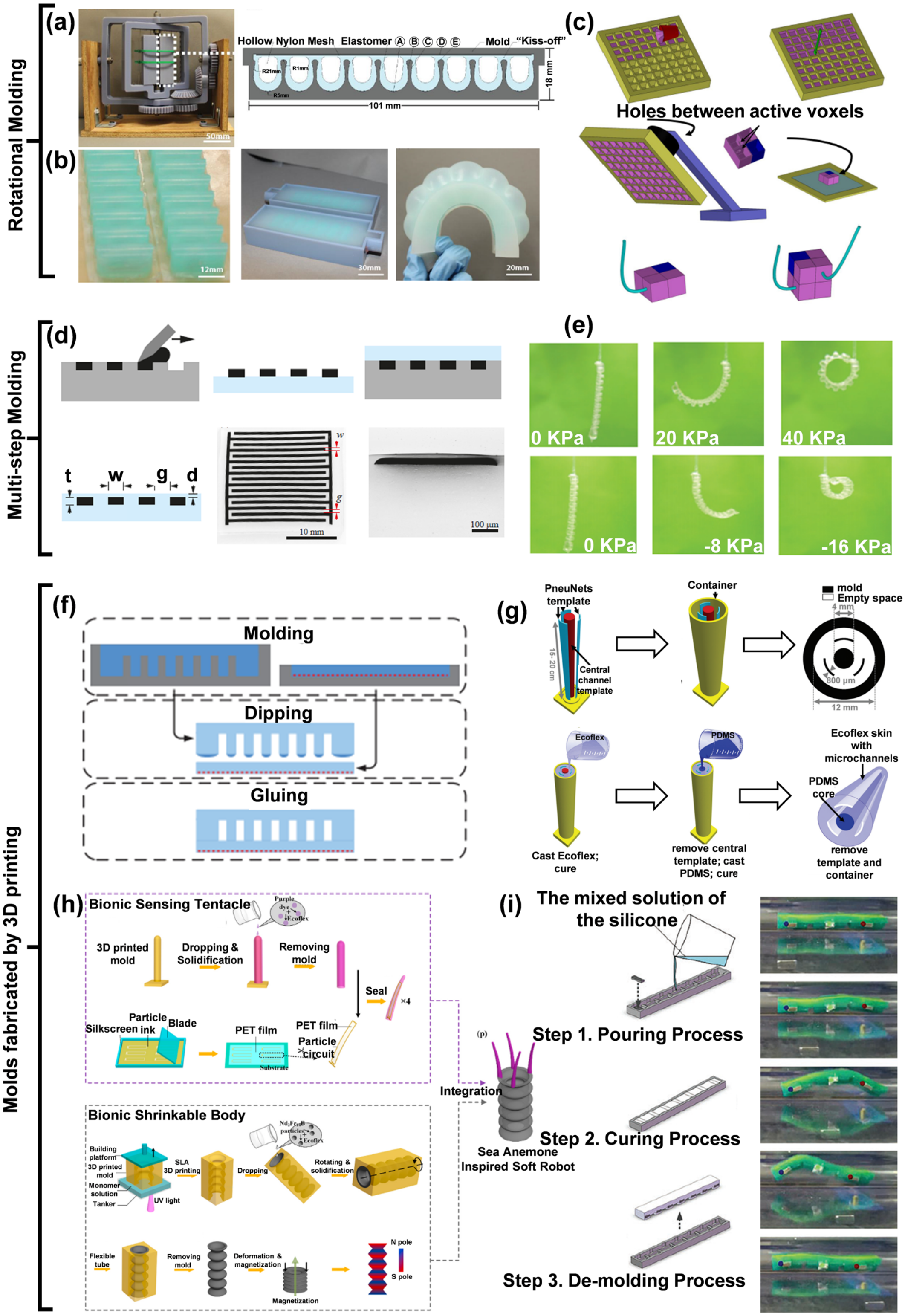


Fig. 1 (a) Rotational cast machine and the interior structure of a cuboid soft actuator mold and elastomer coating. (b) Cuboid actuator casting process and finished inflation actuator.[78] Copyright 2015, Elsevier. (c) Process for manufacturing modular soft robots.[79] Copyright 2020, IEEE. (d) Schematic of the fabrication process of stretchable electro adhesion materials for soft robots.[80] Copyright 2014, IEEE. (e) Experimental results of curling actuators fabricated by molding with positive and negative pressure.[32] Copyright 2008, IEEE. (f) Schematic of the fabrication procedure of fluidic elastomer actuator modules.[81] Copyright 2012, IEEE. (g) Fabrication process of the 3D tentacles. Firstly, preparation of the mold by 3D printing, then two different materials are poured into the mold, and finally the 3D tentacle is obtained by demolding.[82] Copyright 2012, Wiley-VCH. (h) Process for the fabrication of soft robots inspired by sea anemones.[83] Copyright 2021, Elsevier. (i) Process for the fabrication of soft robots inspired by worms.[84] Copyright 2020, Mary Ann Liebert, Inc.

such as on the micro scale. Generally, the preparation methods are also suitable for improving large macroscope soft robots (such as millimeter, centimeter level), which can be understood as modifying the structures of soft objects with external assistance to achieve hyperfine structures with simple steps. However, the cost of the required equipment is relatively high and the operation of the devices sometimes require a specific environment.[86–88]

Etching technology removes materials *via* a chemical reaction or physical impact. Etching plays an essential role in the preparation of soft robots with complicated structures.[89,90] Farrow *et al.* used PCB etching technology to apply patterns on a conductive fabric base material, resulting in different conductive surfaces in the same textile. They connected the distinct conductive surfaces *via* a flexible wire bus embedded in silicone and terminated it in a flexible PCB. The collection of soft capacitive sensing strips and soft pneumatic actuators with embedded sensors manufactured with PCB etching technology is shown in Fig. 2a. The prepared soft robotic could use capacitive touch sensing to interact with conductive objects in the environment. When the actuator was inflated from 5 psi to 6 psi, the actuator successfully pushed a metal can to the left, and when the actuator was deflated to 5 psi, the actuator no longer touched the can (Fig. 2b). The dependence on conductive objects may be a possible limitation of the capacitive pre-touch sensing approach. However, this can be leveraged as an asset in some applications.[91]

Regarding the fabrication and synthesis of soft robots, the laser method can be divided into different forms such as laser etching,[92] laser imaging,[93] laser ablation,[94] and laser cut.[18] Different laser technology preparation methods are employed for different materials and required structures. Jiang *et al.* used the laser-etching method to prepare individual patterns in a stretchable hydrophobic smart film, which was fabricated using a graphene-polymer/SiO_2 composite. The film possessed variable surface wettability and excellent stability to high tensile strain, exhibiting broad application prospects in soft robots (Fig. 2c).[92] Alternatively, for the fabrication of relatively

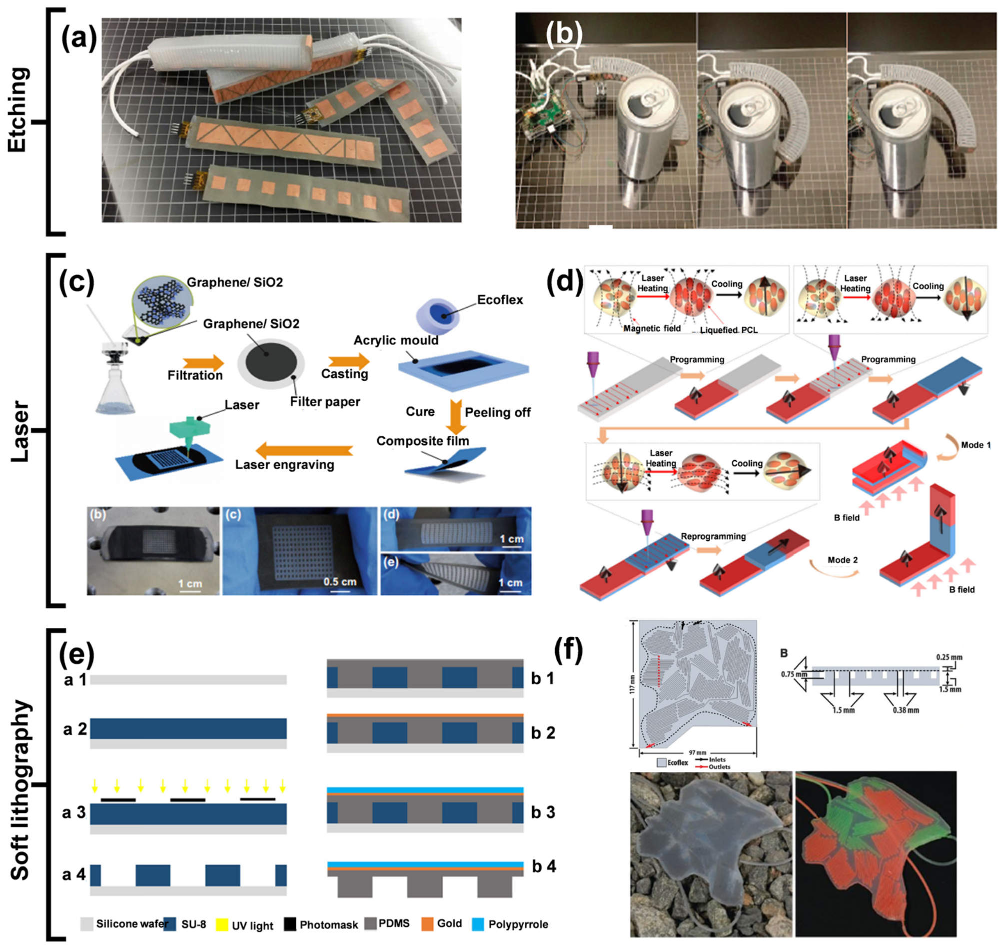


Fig. 2 (a) Pictures of embedded sensor manufactured by PCB etching technology. (b) Sequence of images accompanying the interactive experiments using the objects.[91] Copyright 2017, IEEE. (c) Fabrication process and pictures of the stretchable hydrophobic smart film.[92] Copyright 2019, Springer Nature. (d) Fabrication process of the soft gripper and the experiment and the FEA simulation schematics.[95] Copyright 2020, Springer Nature. (e) Schematic process flow of the actuator. Spin-coating of photoresist SU-8 on a clean silicon substance, and subsequently UV exposure to dissolve uncured photoresist. PDMS is poured and a thin layer of gold evaporated. Then, a thick layer of polypyrrole is electropolymerized. Finally, careful release of the PDMS layer from the silicon substance.[98] Copyright 2019, Springer Nature. (f) Design and operation of the color layer of the soft robot.[101] Copyright 2012, the American Association for the Advancement of Science.

large soft robotics, laser cutting is an economical and flexible option. Tolley *et al.* used molds assembled from 6 mm-thick acrylic laser cut sheets to prepare a resilient, untethered silicone composite quadrupedal soft robot (×0.65 m in length), which had strong pressure resistance and could adapt to various environments (indoors and outdoors).[18] Yang *et al.* used laser cutting technology to fabricate a soft gripper, which was inspired by a thin and elastic kirigami shell. By combining experiments, finite element simulations, and theoretical modeling, the design of the gripper was both scalable and material independent.[48] There is an interesting work related to sample preparation by laser, where Deng *et al.* prepared a special laser rewritable magnetic composite film that could be digitally and repeatedly reprogrammed by the direct laser writing method. The composite film was composed of an elastomer and magnetic particles encapsulated by a phase-change polymer. When laser irradiation generated heat, the orientation of the magnetic particles could be rearranged according to the changes in the programmed magnetic field. By encoding an anisotropic magnetic field in the composite film, the film could generate multimodal 3D shaping by the same magnetic field (Fig. 2d). This work has an important guiding significance for the preparation of reconfigurable soft robots.[95]

As a non-lithographic strategy, soft lithography is based on self-assembly and replication molding for both micro- and nano-processing. The non-lithography technique achieves an optical lithography resolution of 0.1 μm by using a scanning step lithography machine with a large numerical aperture and a deep ultraviolet light source, combined with a phase-shift mask, optical proximity effect correction and double-layer glue.[96] Gradually, it is becoming one of the most common approaches to prepare soft elastomer robots due to its characteristics of being convenient, efficient, and low cost to manufacture micro- and nanostructures.[97] The simplicity of soft lithography allows rapid iterative design. With reference to this feature, Shepherd *et al.* used soft lithography technology to prepare a pneumatic soft robot with complex motions.[3] Tyagi *et al.* employed soft lithography to pattern and fabricate polydimethylsiloxane layers with a geometrical pattern, and they used this technology as a construction element to prepare micro actuators. The process flow of the actuator is shown in Fig. 2e. They successfully controlled the bending angle by choosing the pattern direction (cut) relative to the flexible and rigid elements and designing the thickness and spacing of the flexible and rigid sections.[98] Vergara and co-workers used soft lithography to produce composite elastomeric hollow cubes and permanent magnets, which were used as a passive docking mechanism. They used the coordinated inflation/-deflation mechanism of the modules to separate, connect, and even rearrange the spatial positions of the modules. This research result proposes a new way to produce cheap but powerful synthetic morphogenetic systems and provide new tangible models of cell behavior.[99] Ilievski *et al.* embedded pneumatic networks (PneuNets) of channels in elastomers (PDMS and Ecoflex 00-30) for actuation. They applied soft lithography and microfluidics technologies to construct soft robotic PneuNets. The gripper made of PneuNets was composed of three layers, which could provide a wide range of non-linear motions.[100] In an interesting study, Morin *et al.* used soft lithography adapted from microfluidics to prepare a color-changing soft machine composed of soft polymers and flexible reinforcing sheets (Fig. 2f). The color, contrast, pattern, appearance shape, luminescence and surface temperature of the soft machines used for camouflage and display could be changed through the microfluidic network, which is of great significance in anti-counterfeiting and other fields.[101] It can be seen from above discussion that soft lithography technology plays an important role in the design and manufacture of pneumatically actuated soft systems using composite materials composed of silicone polymers and elastomers.

A study combined lithography with other technologies (such as mold-assisted lithography) to fabricate and synthesize soft robots. Mosadegh *et al.* used 3D printing to prepare basic molds, and then used these molds to fabricate soft robots fPNs with a pneumatic network *via* soft lithography, where the digital syringe pump provided a constant flow rate for both the inflation and deflation of the fPNs. The fPNs actuated quickly and compared with previous similar soft robots, the large size and power-consumption of the fPNs were reduced, while their durability performance was improved (within a million cycles of full bending).[102]

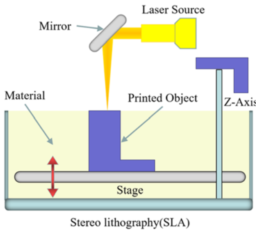
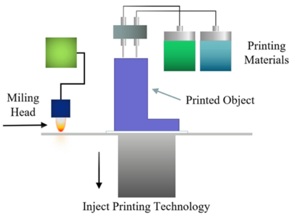
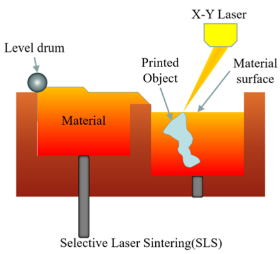
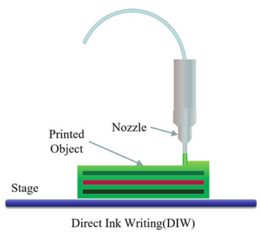
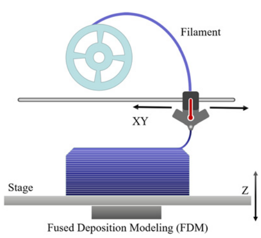
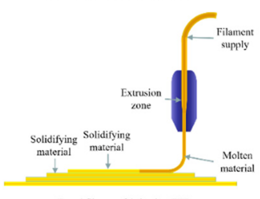
In summary, etching, laser, and soft lithography can be considered as top-down preparation methods. They are suitable for the preparation of both micro soft robots and large soft robots with good accuracy by removing extra materials. However, the cost of their preparation is relatively high. These approaches play an important role in the fabrication and synthesis of soft robotics.

2.3 3D printing/4D printing

Additive manufacturing (also called 3-dimensional (3D) printing) is well known for its efficient assembly of objects layer-by-layer from smaller pieces of materials. However, 3D printing has certain material requirements, such as the size and uniformity of the particles of the materials, good fluidity, and certain curing properties.[103–106] In recent years, 3D printing technologies have been widely used for the preparation of soft robots. 3D-printed products have the characteristics of high quality, low cost, environmentally and ecologically friendly nature, *etc.* Umedachi *et al.* fabricated the first shape memory alloy (SMA) actuated soft robot by 3D printing.[107] Yirmibesoglu *et al.* compared the performance of a 3D printed two-part platinum-cured silicone material soft function robot with molded counterparts, and the results showed that the soft robot prepared using a 3D printer with an enhanced extrusion mechanism was stronger and more reliable.[108] The categories, advantages, and disadvantages of these 3D printing technologies are shown in Table 1. Different categories of 3D printing technologies have different scopes of application.

The cost of the conventional photolithography technique is high and it requires clean room facilities. Alternatively, the stereolithography (SLA) technique appears to reduce the complexity of the fabrication of soft robotics. It is worth noting that there are certain requirements (such as elasticity, viscosity, and composition) for the selection of polymer materials for

Table 1 Summary of soft robots fabricated by 3D printing

Category	Schematic diagram	Advantages	Disadvantages	Materials	Ref.
Stereo-lithography (SLA)		Precise control, make the most of materials, rapid polymerization, and prints materials with multiple attributes.	Support required, unused materials are toxic and flammable, warping, and sticky unused materials.	PEGDA-collagen hydrogel Resin vat constructed from borosilicate glass with a thin layer of Sylgard 184 (PDMS). Poly(mercaptopropyl) methylsiloxane-*co*-dimethylsiloxane and PDMS. Spot E elastic resin, EMG 1200 dry magnetic nanoparticles.	111 112 114 116
Selective laser sintering (SLS)		No support required and parts with high mechanical properties.	Printing equipment is relatively large and expensive.	Elastic silicon materials A polymer powder named PA 2200 with a particle Graphite, PA12	122 123 124
Shape deposition modeling (SDM)		Fabricates complex geometries with heterogeneous materials and rapid prototyping.	High control is required.	Task-9TM polyurethane (stiff segment), PMC-780TM urethane rubber (flexible segment) Two parts of industrial polyurethanes, IE35A, IE90A, IE72DC	128 129
Fused filament fabrication (FFF)		Providing viable and cost-effective solutions for design validations, the fabricated production with high-performance, and materials and printing flexibilities.	Poor finish, geometrical fits and tolerances, anisotropy, in-printing errors, and limited mechanical strength.	Thermoplastic elastomers (TPE), FilaFlex Acrylonitrile styrene acrylate thermoplastic filament Printer filament polylactic acid or acrylonitrile butadiene styrene (PLA or ABS) Thermo-reversible Diels–Alder DA polymers Thermoplastic elastomers (TPE) filament Polyurethane Thermoplastic 95 (TPU 95A), a low-friction polyurethane thermoplastic	133 135 136 138 139 140
Inkjet Printing		Mask-less non-contact deposition technique, rapid mass production, high levels of production accuracy, arbitrary geometries, and low cost.	The nozzle is easily clogged.	Silver ink Flexible silicone rubber, Galinstan, and copper. 3 wt% carbon black powder, 26 wt% silicone polyglucoside dispersant, and a siloxane solvent. Resin	143 144 145 146
Direct writing (DIW)		Convenient and easy to operate and rapidly patterns functional materials in complex 3D architectures from a broad array of materials.	The nozzles need to be improved to achieve large-scale production.	Rubber-like digital material (FLX9085-DM) Electrically insulating silicone and an ionically conductive hydrogel.	149 150

stereolithography.[109,110] Chan *et al.* incorporated acrylic-PEG-collagen in a photopolymerizable PEGDA hydrogel (PEGDA-PC) and used the stereolithography technique (layer-by-layer UV polymerizable rapid prototyping system) to fabricate multiple-material hydrogel actuators and cantilevers, which exhibited an elasticity of up to 103 kPa (Fig. 3a). The cantilever prepared by this work is as compliant as the cantilever of the native myocardium, which is an early prototype for designing optimal cell-based biohybrid actuators.[111] Peele *et al.* used the stereolithography technique to prepare artificial muscles with soft

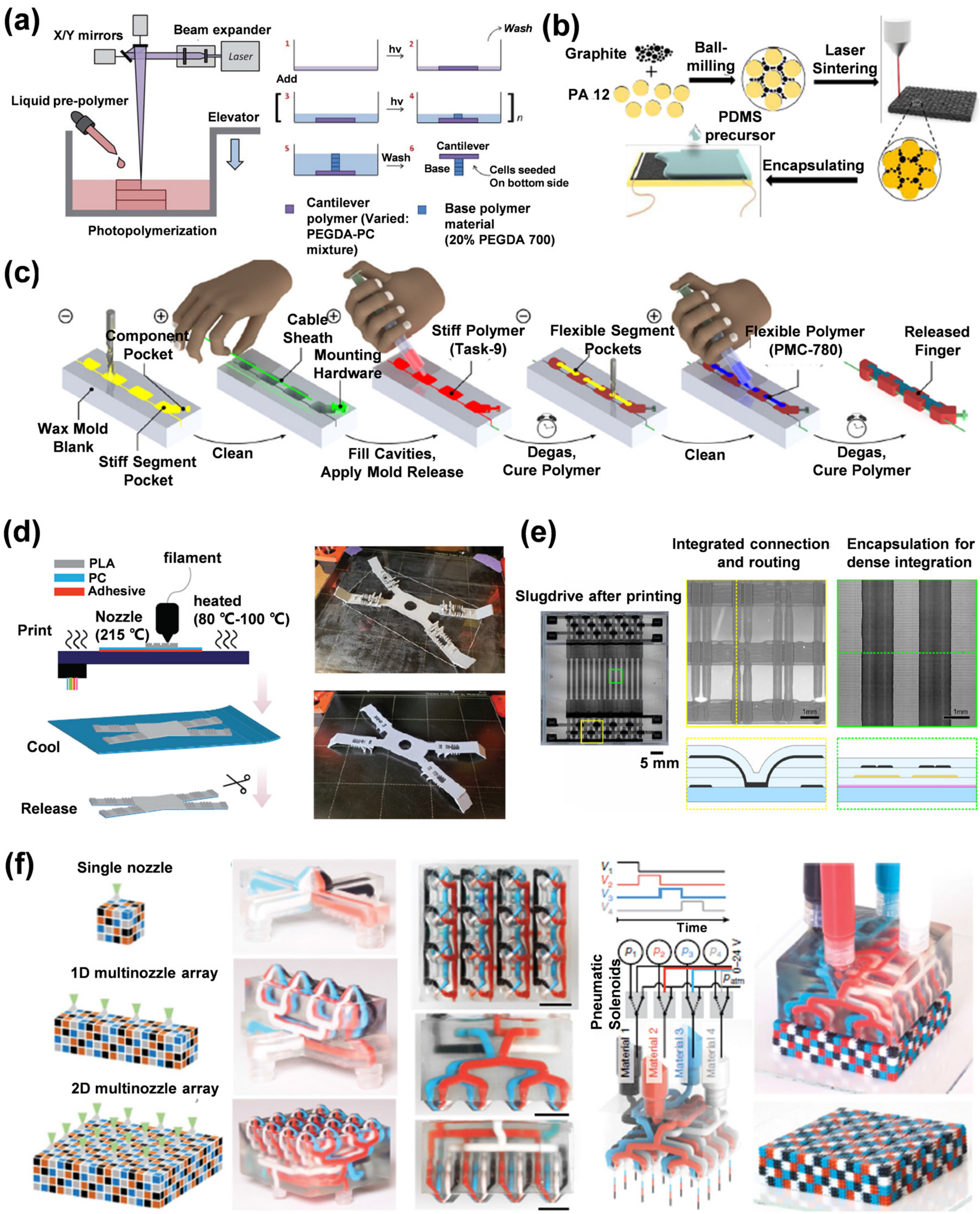


Fig. 3 (a) Schematic diagram of multi-material cantilever fabricated *via* SLA.[111] Copyright 2012, The Royal Society of Chemistry. (b) Schematic of the fabrication process of the composite-material sensor through SLS technology.[124] Copyright 2019, The Royal Society of Chemistry. (c) Overall process for the preparation of a finger model using the SDM method.[128] Copyright 2015, ASME. (d) Use of the FDM method to prepare a flexoskeleton and physical display.[136] Copyright 2020, Mary Ann Liebert, Inc. (e) Densely integrated images of actuators prepared by inkjet printing.[145] Copyright 2020, Wiley Online Library. (f) Schematic diagram of MM3D process.[151] Copyright 2019, Springer Nature.

structures, which could interact and mimic biological systems.[112] Shiblee *et al.* printed a shape memory hydrogel (SMG) using stereolithographic technology to fabricate two different samples, with different concentrations of stearyl acrylate (SA) and dimethyl acrylamide (DMAAm) monomer. This is novel technology for the preparation of SMG actuators.[113] In addition, it is expected that some accessories prepared using SLA will be used in the field of soft robotics.[114–116]

Selective laser sintering (SLS) is 3D printing technology that uses a laser as the power source to sinter powered materials. SLS is suitable for the rapid prototyping of powders and the preparation of small-volume productions, and the fabricated products usually have high mechanical properties.[117–119] As a novel, facile and low-cost selective laser-sintering strategy, some software devices such as grippers are prepared by SLS.[120,121] Rost *et al.* fabricated a multi-finger soft robotic hand with 12 degrees of freedom by SLS.[122] Roppenecker *et al.* prepared a multi-arm inspired by snakes, and the structures made by SLS could bear weight of around 800 g, which may helpful in performing surgery inside the stomach tract.[123] In addition, Wei *et al.* used SLS technology to prepare soft conductive films by sintering a nylon and graphite mixed powder, and their preparation process is shown in Fig. 3b. This film had good flexibility and allowed a variety of somatosensory capabilities to detect touch, stretch and bending. The strategy for preparing actuators in this work is efficient and direct. The entire preparation avoided the use of solvents, which meets the requirements of green chemistry for the manufacture of functional materials.[124]

The process of shape deposition modelling (SDM) is repeated until the final layer is reached, which is an important method to prepare soft elastomer robots.[125] In the early days, the emergence of SDM enabled the development of soft robots with compliant mechanisms and embedded sensors and actuators, such as iSpurl[126] and Stickybot.[127] Due to the fact that some polymer materials have better curing and modelling properties, SDM also plays a certain role in the preparation of graspers.[128,129] Gafford *et al.* used SDM to prepare a multijointed grasper frame. The prepared gripper did not use friction or pinching but used geometric trapping to manipulate tissues. The prepared soft robot eliminated the possibility of intraoperative complications caused by sharp, rigid tools and lack of tactile feedback during robotic laparoscopic surgery by providing a soft interface between current tools and fragile tissues (Fig. 3c).[128]

The smart composite microstructure (SCM) preparation method is complementary to SDM. SCM can be considered as a preparation method that combines cutting and lamination, which is suitable for the preparation of small-scale biomimetic robots. For meso-scale robots, compared with traditional rotating joints, flexure joints have smaller friction and simple structures.[40]

Fused deposition modelling (FDM) is one of the most popular 3D printing technologies due to its low cost and straightforward procedure, which has been widely used in industrial applications and become the most accessible 3D printing alternative for the general public.[130] Recently, research on the preparation of sensors with FDM technology has been reported, which is of great significance for the future application of soft robots.[131,132] Some soft robots fabricated with FDM technology have realized functional applications and successfully achieved grasping[133] and actuating.[134] In addition, Teoh *et al.* fabricated an undulating soft robot inspired by the knife fish, in which the body casing and flapper were printed using FDM and acrylonitrile styrene acrylate (ASA) thermoplastic filament.[135] Recently, Jiang *et al.* used FDM technology to fabricate hybrid soft and rigid robots. Their work significantly improved the fatigue resistance of printed components and achieved a new class of robot forms inspired by insects (Fig. 3d).[136] With the improvement and maturity of FDM technology, it has also played a very important role in 4D printing.[137] Fused filament fabrication (FFF) with the same printing principle as FDM is also known as FDM. It is a preparation form of 3D printing with vat polymerization and powder bed fusion. In recent years, some soft robots have been fabricated by FFF; however, it still needs to be strengthened in terms of finish, geometrical fits and tolerances, anisotropy, *etc.*[138–141]

Inkjet printing, as 3D printing technology, is a digital printing process to print a digital-based image directly by depositing small droplets of ink in rapid succession.[142] Due to the fact that inkjet printing can mass-produce high accuracy productions at low cost, it is used to fabricate sensors, such as soft tactile sensors[143] and wearable sensors.[144] Schlatter *et al.* used inkjet printing to fabricate complex soft machines with densely integrated electrostatic actuators, which may provide an important foundation for the preparation of future sensors. The cross-sections and close-ups of electrical vias and high-voltage zipping electrodes of the actuator illustrate the superior performance of inkjet printing technology (Fig. 3e).[145] MacCurdy *et al.* proposed a new inkjet printing process that uses liquid and solid components to simultaneously manufacture the required 3D objects. They called it a printable hydraulic system, which can be completed by different functions of a hydraulically driven soft robot structure. Also, they successfully prepared a hydraulically driven hexapod soft robot.[146]

Direct ink writing (DIW) is a preparation method for the translation stage controlled by a computer, creating a controlled architecture and composition of materials through the ink deposition nozzle.[147] DIW can rapidly achieve patterned functional materials in complex 3D architectures from a broad array of materials. However, in the case of large-scale production, the nozzles need to be improved.[148] Mark *et al.* used two 3D printed metamaterials with auxetic and normal elastic characteristics to prepare a soft robot through DIW technology. The soft robot used mechanical metamaterials to achieve the internal synchronization of the two passive clutches contacting its traveling surface. This enabled it to move through a closed channel by the movement of an inch worm driven by a single actuator.[149] Robinson *et al.* used two inks by DIW technology to demonstrate an artificial equivalent of a sensory motor on soft, fluidic elastomer actuators (FEAs). The sensors were fabricated to allow tangible perception and kinesthetic responses in pneumatically stimulated tactile devices. According to the report, the capacitive skin could detect a generated pressure of $\sim$2 N by pressing its top surface with a finger, and the internal pressure was around 10 kPa.[150]

DIW is a convenient approach to fabricate samples by extruding monolithic cylindrical filaments in a layer-by-layer manner. However, it is difficult to generate multi-material voxelated matter using this method. Accordingly, Skylarscott *et al.* designed a method called multi-material multi-nozzle 3D (MM3D) printing to solve this problem, which is of great significance to the field of 3D printing of soft robotics (Fig. 3f). This research helped to eliminate the periodic constraints imposed by the print head design, thereby improving the feature resolution and reducing the build time. It is expected to efficiently achieve the on-demand creation of 3D voxelated substances with excellent performances in the future.[151]

Subsequently, as the primary offshoot from 3D printing, 4-dimensional (4D) printing emerging due to the programming of physical and biological materials, which is the key of this technology.[152] The fourth dimension means that the objects printed can change their structures over time, including shape, physical property, and functionality. Specifically, when objects are exposed to external stimuli (such as thermal, photosensitivity, moisture, electronic, magnetic, chemical, light, mechanical, pH, pneumatic and other energy sources), their structures change.[153,154] However, a significant challenge associated with this feature is the choice of materials. The SRMs that change with external stimuli occupy an important place in this field, which can usually be divided into external and internal triggers. The components fabricated of soft robots under different mechanisms have various application prospects in the field of soft robotics. Light (UV light and laser beam), magnetic field, electric field, *etc.* can be classified as external triggers. Controllable or voluntary chemical reactions are classified as internal stimuli-responsive systems.[155] In addition, SMMs are a type of material that undergo reversible deformation due to martensitic transformation, which can usually be divided into SMAs, SMPs, shape memory composites (SMCs), and shape memory hybrids (SMHs). These materials can change over time when the external environment changes, and therefore they have broad application prospects in the field of 4D printing preparation soft robots.

In recent years, among the materials of soft robots that respond to the external environment, there is a relatively large amount of research on thermal response, including elastomers,[156] hydrogels,[157] and SMPs combined with other functional materials.[158,159] There is also some research on multi-responsive soft robots fabricated by 4D printing. Jin *et al.* fabricated a crystalline SMP-based single-component soft robot, which exhibited a performance of both thermal- and photo-reversible characteristics.[160] Liu *et al.* used SMPs with magnetic microparticles to fabricate composite films that can respond to photothermal and magnetic stimuli. In this study, composite films were used in reconfigurable and remotely actuated soft robots. However, to obtain reconfigurable behavior in the system, multiple-stimuli need to be present simultaneously.[161] In addition, some studies on soft robotics used 4D printing technology. These soft robots have good application prospects in the biomedical field.[162–164]

In summary, the emerging fabrication approaches provide solutions to design complex structures (shape, physical property, functionality, *etc.*) of soft robots. 3D printing technologies have become more mature, their cost has been reduced, the preparation has become convenient, and have gradually been widely used in production. Alternatively, 4D printing technology and smart materials play an important role in the preparation of some parts of soft robots, which is a further development prospect in the field of soft robots.[165,166]

2.4 Others

In addition to the above-mentioned currently commonly used approaches for the fabrication and synthesis of soft robots, other methods (reinforcement,[62,167] thin-film manufacturing,[168] architectural considerations,[169] *etc.*) are also applied in this field.

To meet the requirements of relatively complex design functions, it is necessary to combine multiple fabrication and synthesis methods when preparing soft robots. For example, Wehner and co-workers fabricated a completely soft and autonomous robot *via* hybrid fabrication technology inspired by the octopus. The integrated design strategy included molding (body), soft lithography (microfluidic logic), and multi-material-embedded 3D printing (pneumatic actuator networks, on-board fuel reservoirs and catalytic reaction chambers). The rapid manufacturing method and integrated design proposed in this study are helpful for the programmable assembly of multiple materials in a single body, providing a notable idea.[170]

In this chapter, some approaches used to prepare soft robots are classified and introduced (Table 2), and some typical examples are explained in detail. We divide the fabrication and synthesis methods of soft robots into top-down (molding, etching, laser soft lithograph, *etc.*), bottom-up (3D printing, 4D printing, *etc.*), and a combination of multiple approaches. The content of this chapter has important reference value for the fabrication and synthesis of soft robotics in the future.

3. Soft robot driving strategies

Driving soft robots is a necessary step for them to exert their functional characteristics. Thus, in this chapter, we introduce

Table 2 The advantages and disadvantages of the approaches for the fabrication of soft robots

Fabrication approaches	Advantages	Disadvantages
Molding	Low cost, simple production process, more convenient and rapid to prepare.	It is difficult to manufacture internal volumes, undercuts, and complex internal structures and need to remove bubbles generated during the molding process.
Etching Laser Soft lithography	They are suitable for the preparation of both micro soft robots and large soft robots with good accuracy by removing extra materials.	The cost of equipment is relatively high, and the operation of the devices sometimes needs certain environment requirements.
3D printing 4D printing	High quality, low cost, and environmentally and ecologically friendly.	The materials that can be printed have limitations.

the driving strategies of soft robots. We divide them into two major directions, *i.e.*, actuator-based driving strategies and materials-based driving strategies.

In terms of actuator-based driving strategies, the actuator plays a vital role in the actuation of soft robots. The shape, structure, and distribution position of the actuators determine their functional characteristics to some extent. In a previous review on actuators, El-Atab *et al.* reviewed the different soft actuation methodologies and their various applications in soft robotics.[171] Marchese *et al.* reviewed soft robotic actuators from two aspects, *i.e.*, their operating principles and morphologies. The morphologies included the design and the fabrication of three different soft fluid elastomer body segments, *i.e.*, ribbed, cylindrical, and pleated.[172] In this section, we mainly summarize the types of actuators, including soft pneumatic actuators (SPAs), elastomer actuators (EAs), and others.

Regarding material-based driving strategies, the actuation of soft robots is realized by driving deformation under the stimulation of the external environment (such as thermal, magnetic, electric and light). In this section, we introduce indirect drive material elastomers and the direct drive material SRMs and SMMs.

3.1 Actuator-based driving strategies

Soft robots realize complex movements such as crawling, grasping, jumping, and swimming through bending deformations.[173–175] Accordingly, the introduction actuators is one of the most common driving strategies in soft robotics, which allows soft robots to complete different actions and tasks without complex structure design. However, the relatively large size of actuators limits their application in nano-/micro-scale soft robots and delicate applications including surgery and fabrication of nano-/micro-materials.[176–178] Recently, soft pneumatic actuators (SPAs) and elastomeric actuators (EAs) have become the prevalent actuation strategies for driving soft robots.[32] In this section, we mainly summarize these two aspects, and at the end of the section, we describe some other types of actuators.

3.1.1 Soft pneumatic actuator-based driving strategy. The use of soft actuators has become a vital strategy to drive soft robots because of their ingenious design structure and flexible degree of freedom. Conventional soft actuators have shortcomings in terms of robustness, repeatability, controllability, and force output performance. Soft pneumatic actuators (SPAs) can solve the above-mentioned problems to a certain extent, while meeting the reliability standards of soft robots. The in-depth development of SPAs is conductive to the development of new soft robots in the direction of safety, adaptability, and customizability.[17,179,180]

At present, SPAs are made entirely out of soft materials, and therefore are inherently soft and vastly customizable. Different forms of SPAs can be used in different cases. Sun *et al.* presented the characterization of two different types of silicone rubber-based SPAs, *i.e.*, bending and rotary. The bending movement of bending SPAs is similar to the movement of a human finger and can be constructed in a bundle to form an artificial muscle that contracts upon inflation. Alternatively, rotating SPAs can be used as an active hinge for small robotic equipment. Through the design and analysis of SPAs with origami shell reinforcement, Paez *et al.* found that when the shell provides reinforcement, the performance of the bending module significantly improved. With the help of the shell, the bending module could withstand higher inflation pressure, delivering large blocked torques and generating targeted motion trajectories.[181]

To improve the performance of soft robots with pneumatic actuators, some researchers have also modified the actuators. Shepherd *et al.* used a silicone elastomer with polyaramid fibers to fabricate a below-like gripper, which could pick up a wine glass either from the inside or the outside by bending bidirectionally using positive or negative pressure. The gripper increased the tear resistance and had self-healing ability through small punctures.[182] Yi *et al.* reported the fabrication of a pneumatic soft linear actuator fiber-reinforced origamic robotic actuator (FORA). The design and fabrication of FORA are shown in Fig. 4a. This new type of actuator can provide nearly double the range of motion and significantly improve the force distribution and reduce the driving pressure. FORA combined this new origamic chamber with a reinforced fiber mesh to achieve high traction (over 150 N) and large contraction motion (over 50%) under low input pressure (100 kPa). Also, the quasi-static analysis model was developed to characterize the movement and force to achieve the guidance of the actuator. As shown through experimentation, the actual performance of FORA is consistent with that predicted by the model. FORA has a wide range of application prospects in soft robotic systems due to its unique mechanism, easy preparation, and ideal performance in the future.[183] Fiber-reinforced elastomers led to the development of the design and mechanical properties of soft robotics.[184]

To improve efficiency of soft actuators, iterative optimization through simulation has been employed to design soft actuators that meet the specified performance indicators and geometric constraints.[185] Moseley *et al.* applied the finite element method to provide a comprehensive open-source simulation and design tool for SPAs, which is compatible and expandable to various soft materials and design parameters. They carried out finite element simulation analysis on linear SPA and bending SPA. Regarding to the simulation and experimental results of linear SPAs, at low and medium pressure, the predicted results of various dimensions in the displacement testing were consistent with the experimental values. Also, the results of the block-force of the linear SPA in FEM and experiment were similar. When the pressure was less than 30 kPa, the simulations showed higher forces than the experiments, before a sharp increase in force was observed in both the experiments and simulations (Fig. 4b). The data of bending angle and blocked-force of the bending SPAs showed that the simulations match the experimental results at low pressure and captured the experimental trends at high pressure where significant rotation occurs (Fig. 4c). These analysis results showed that the complex effects of SPA can be analyzed, and thus the shape and design of actuators can be better created to resist failure. This is a good application of simulation methods in the actual design of SPAs and fully demonstrates that combining simulation can improve the

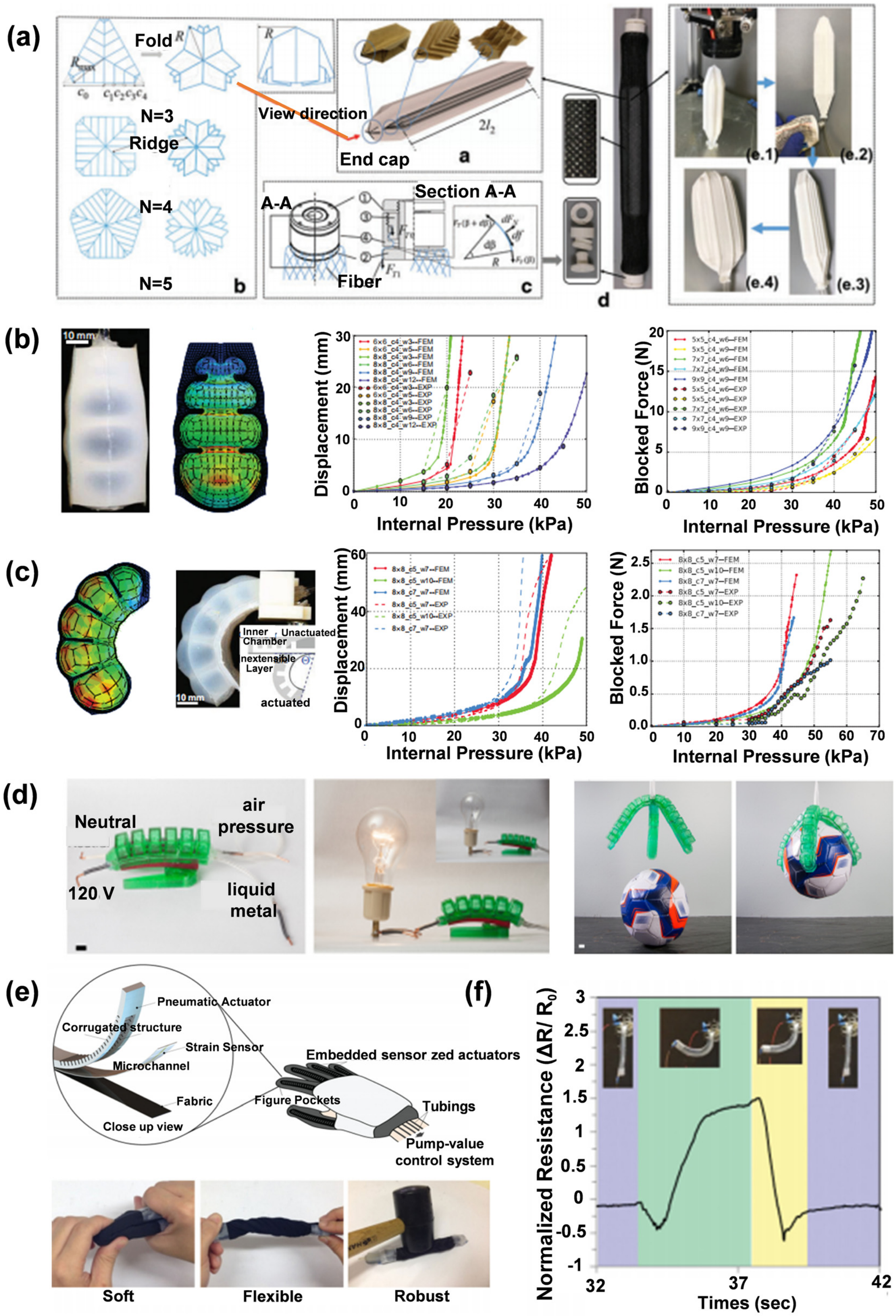


Fig. 4 (a) Design and fabrication process of FORA. This figure shows the concept of the origami chamber with basic origami patterns, schematic of the end caps of the origami chamber with a different number of ridges, schematic design of the connection fittings, the fabricated prototype of FORA, and fabrication process of the origami chamber, respectively.[183] Copyright 2018, Mary Ann Liebert, Inc. (b) Finite element analysis of linear SPA. Comparison of simulation and experimental results under various dimensions in displacement testing and blocked-force testing. (c) Finite element analysis of bending SPA. Comparison of simulation and experimental results under various dimensions in displacement testing and blocked-force testing.[186] Copyright 2016, WILEY-VCH. (d) Pictures of pneumatic switch that can power light bulbs and large soft gripper with three independent control arms to grab a soccer ball.[188] Copyright 2021, the American Chemical Society. (e) Picture of applying the actuator in a glove to facilitate data collection and the data diagram of the corresponding electrical signal when the actuator is bent. Also, the pictures well show that the actuator has the characteristics of soft, flexible, and robust. (f) Electrical signal corresponding to one actuator bending.[189] Copyright 2016, WILEY-VCH.

design and preparation efficiency of SPAs.[186] Finite element simulation or related software analysis was applied to design SPAs in advance, and then real soft robots were prepared to meet the specific performance and constraints. Chen *et al.* designed an SPA that is a bionic human esophageal peristalsis. Multi-layer inflatable chambers were regularly embedded and distributed along the axis of the food passage, which was located in the center of the actuator. Firstly, they used finite element analysis and simulation to help structural design, and then prepared molds to pour silicon rubber through 3D printing. They studied the shrinkage performance of the soft pneumatic actuator through experiments, and the results showed that the shrinkage of the silicon tube was mainly determined by the local cavity.[187]

In addition to the above-mentioned descriptions, some soft robots are designed to combine SPAs with other technologies, devices, and mechanisms to prepare new types of multi-functional and expandable comprehensive soft robots. Gomez *et al.* proposed an elastomer system with a vat photo-polymerizable self-healing property that could be elongated ten times that of the original material. The self-healing elastomer was printed by 3D printing technology and combined with a functional liquid metal to fabricate a multi-functional soft robot through modular assembly, which could be used for both grasping and pneumatic light switches (Fig. 4d).[188] Yeo *et al.* proposed a strategy to combine a flexible SPA with a stretchable strain sensor to form a soft sensor actuator. The pneumatic actuator realized bending by connecting an air source. The strain sensor achieved stretchability and flexibility by coating a thin layer of screen-printed silver nanoparticles on an elastic substrate, while maintaining excellent electrical conductivity (at $\approx 8\ \Omega\ \mathrm{sq}^{-1}$) (Fig. 4e). This method has broad application prospects in the field of rehabilitation sensing and the proposed strategy has important inspiration for the combination of soft actuators and other functional devices. The electrical signal generated when the actuator was bent is shown in Fig. 4f.[189] Xu *et al.* built a soft robot that combines a pneumatic actuator and jamming mechanisms. Also, through finite element analysis, they optimized the influence of the pressure in the pneumatic chamber, the shape and size of the chamber on the bending motion performance. The prepared soft robot had the characteristics of variable stiffness and could withstand the variable stiffness of 0.025–0.138 N mm^{-1}, and the designed coupling mechanism could reach a maximum elongation of 25 mm.[190]

In summary, SPAs are a common driving strategy with the characteristics of convenient preparation, easy operation, robustness, reusability, and controllability. Through the simulation, the performance of the design SPAs can be predicted in advance, thereby improving the efficiency and performances of the prepared SPAs. In addition, SPAs can be combined with other technologies, devices, and mechanisms to prepare multi-functional soft robots, which will become the development trend of SPAs in the field of soft robots. However, SPAs usually require numerous pneumatic accessories, which are difficult to miniaturize. The miniaturization of soft pneumatic actuators will also be one of the future research directions.

3.1.2 Elastomeric actuator-based driving strategy. In this section, we mainly introduce two types of EAs, *i.e.*, fluidic elastomer actuators (FEAs) and dielectric elastomer actuators (DEAs).

FEAs are actuators composed of low durometer rubber and driven by a relatively low-pressure fluid in the range of 3 to 8 psi. FEAs can achieve extending, contracting, bending, twisting and other actions. Generally, FEAs use elastomer films with embedded fluidic channels, and the fluid contained in the channel is pressurized to generate stress and local strain in the elastic materials. Accordingly, the combination of the relative inextensibility of stress and strain produces deformation of the elastomer materials. FEAs can be powered pneumatically or hydraulically.[172,191]

Some studies have been carried out to reduce the elastomer strain on the outer layer of actuators.[77,102] Mosadegh *et al.* designed new pneu-nets that reduce the amount of gas needed for inflation and increase the speed of actuation (Fig. 5a). The designed actuator could be bent from linear to the standard quasi circle in only 50 ms, as shown in Fig. 5b (ΔP = 345 kPa). When fully inflated, the volume change of the chamber designed was relatively small, which caused the strain level of the material under the maximum driving amplitude to be relatively low, and the fatigue fracture and failure rate were also reduced. Through the circle test, the performance of the actuator did not change significantly even after running more than one million times (Fig. 5c).[102] Fluid actuators that realize large amplitude motion generally require a large energy supply, and the operating speed and compactness of these actuators are limited. Overvelde *et al.* built a fluid actuator by combining a fluid section with the designed nonlinear response and used fluid to quickly pass-through instability to produce large motion, high force, and fast drive in a constant volume.[192]

Similar to the fiber-reinforced mechanism in the actuator mentioned in the previous section to improve the performance of SPA soft robots, FEA soft robots also apply fiber-reinforced elastomers to improve the overall performance of the system. Feng *et al.* prepared a serial soft actuator array consisting of four fiber-reinforced, bidirectionally curved, fluid elastomer actuators (FEAs) (Fig. 5d). This FEA array could realize anguilliform locomotion. They developed an underwater untethered anguilliform swimming robot and proposed the design and manufacture of a fiber-reinforced bidirectional bending finite element. By measuring the bending angle of the FEA array dynamically loaded in water, it was proven that its performance depends on the driving signal and its position. By comparing the three-dimensional simulation results of the finite element method, it was concluded that the designed FEA array has a good experimental effect (Fig. 5e and f).[193] Moser *et al.* aimed to simplify the design process of soft robots with incompressible fluid, inextensible fibers, and extensible elastomers by capturing interactions as pure geometric relationships. This could predict the direction of deformation of soft robots in advance and determine a feasible topology that meets a series of motion requirements for single and parallel actuator configurations.[194] Galloway *et al.* designed and manufactured a fiber-reinforced soft actuator whose bending radius and bending axis could be

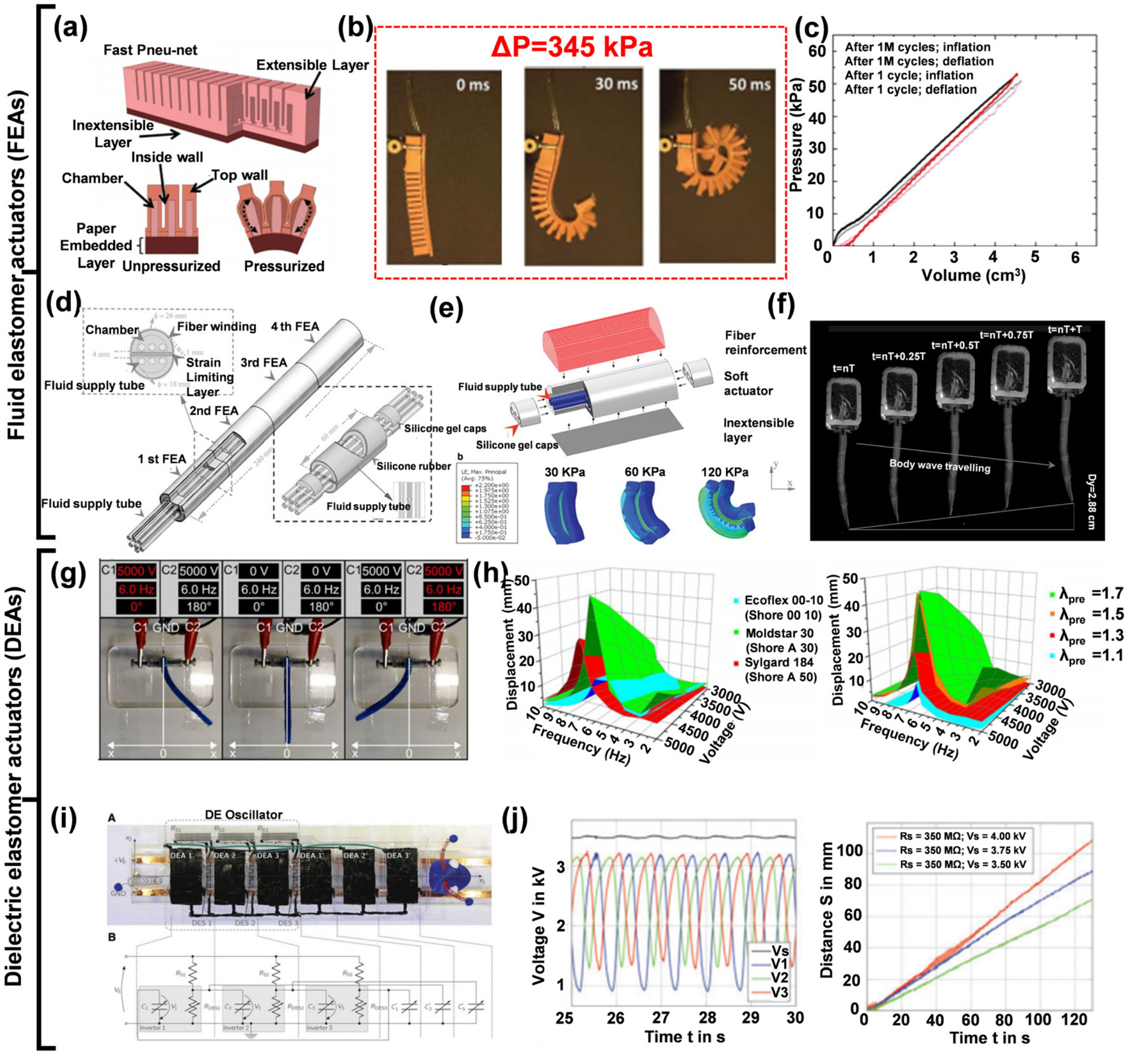


Fig. 5 (a) Schematic diagram of the designed actuator. (b) High-speed video time-lapse image under 345 kPa pressure. (c) Fatigue test of actuator under one million cycles.[102] Copyright 2014, WILEY-VCH. (d) Structure of the FEA array. (e) 3D finite element method model and simulation results of FEAs. (f) Schematic diagram of the underwater swimming soft robot in one cycle.[193] Copyright 2019, Mary Ann Liebert, Inc. (g) Pictures of measuring displacement when running in dynamic or static mode. (h) Research results of dynamic displacement under different silicone main materials (Ecoflex 00-10, Moldstar 30, and Sylgard 184) and different pre-stretching (λ_{pre} = 1.1, 1.3, 1.5, and 1.7).[198] Copyright 2020, Front. Robot. AI. (i) Schematic diagram of the designed structure of the bionic crawling soft robot. (j) Data graph of measured oscillating voltage signal and position of the soft robot under different supply voltages during the experiment.[200] Copyright 2017, Mary Ann Liebert.

mechanically programmed. Experiments verified the feasibility of this method.[195]

Incorporating simulation is also suitable for improving the preparation efficiency and performance of FEA soft robots. Marchese *et al.* developed a software robot control system that could interact autonomously, dynamically, and safely with humans and their environment. They first established a dynamic model and proposed an independent recognition system, and then used the model and trajectory optimization technology to find the local optimal open-loop strategy. The established soft manipulator system was composed of soft rubber with fluid elastomer actuators distributed in it to provide fluid energy. This research proved that the research method of planning and control based on dynamic models can be applied in the design and development of soft robots.[196]

Converting different types of natural motions into engineering motions is a core issue in the preparation of soft robotics by biomimetic phenomena or functional characteristics of natural organisms. Dielectric elastomers (DEs) with the functional characteristics of artificial muscles have the properties of softness, light weight, and large stroke and can exhibit large strains (10–50%) and moderate stress (around 100 kPa), and thus have good application prospect in driving multifunctional bionic mechanisms. DEAs used DEs to directly control the drive of soft robots with electricity in multiple directions, and they have also been widely applied in current research.[197]

Franke *et al.* proposed a soft robot structure with a bionic skeleton integrated into the soft body element, which was driven by an antagonistic working DEA artificial muscle pair. The existence of DEAs caused the soft robot to show anisotropic biological shape bending behaviour. During the experimental evaluation of the robot, they used the classical laminate theory to analyze and model, and through research, various parameters to achieve the optimal design of the actuator performance. The real-time displacement measured by the prepared soft robot is shown in Fig. 5g. The soft robot in this experiment successfully tested the real-time displacement under static and dynamic conditions. Fig. 5h shows the displacement of the soft robot under different voltages and frequencies under three different silicon body materials (Ecoflex 00-10, Moldstar 30, and Sylgard 184) and four different pre-stretching (λ_{pre} = 1.1, 1.3, 1.5, and 1.7) of the DEA silicone membranes with Moldstar 30 as the silicone body material. The system designed in this study will have potential important applications in the fish tail design of bionic fish soft robots in the future.[198] In the case of bionic fish tails, Berlinger *et al.* designed a fin-liked DEA that could drive a miniature autonomous underwater vehicle.[199]

Henke *et al.* prepared a bionic caterpillar soft robot with an integrated artificial nervous system and soft actuators. A schematic diagram of the designed bionic crawling soft robot is shown in Fig. 5i. The prepared soft robot uses a dielectric elastomer oscillator (DEO) to change its electrical resistance and switch charge flow on and off upon mechanical deformation. The soft robot could automatically generate all the signals needed to drive its DEAs after receiving an external DC voltage and converted the in-plane electromechanical oscillations into crawling motion (Fig. 5j). The movement of each DEA muscle was controlled by the mechanical strain of the adjacent muscles. Research shows that designing bionic soft robots with soft actuators and charge control devices is a feasible and promising research direction.[200]

Nguyen *et al.* prepared a hexapod-driving walking soft robot inspired by insects. A 3D printing method was used to embed a dielectric elastomer actuator with an antagonistic configuration in a soft robot and develop a control system. The final prepared soft robot could successfully adjust the speed and stride lengths.[201]

Godaba *et al.* realized the use of DEAs to drive in the designed submarine soft robot inspired by jellyfish. When the DEA was subjected to a voltage, the membrane expanded, the volume of air increased, and the buoyancy force acting on the robot increased. Simultaneously, water was sprayed from the body of the robot, which could induce the robot to move upward. They analyzed the performance of the actuator through theoretical simulation, and the results were consistent with the experimental results.[202]

However, the use of DEAs also has certain limitations. DEAs are affected by high temperature to a certain extent, and when the designed electric signal system interaction and control are complex, the measurement accuracy will be reduced. Hajiesmaili *et al.* introduced the characteristics, design, operation, and influencing factors of DEAs in detail from the perspective of physics, providing a theoretical basis for the design of DEAs that are more suitable for use in the field of soft robotics. Improving the uniformity of the motor, reliability of the actuator, and developing higher dielectrics are the areas where DEAs will be used in soft robotics in the future.[203]

In summary, in this section, we introduced two elastomer actuators, *i.e.*, FEAs and DEAs. FEAs can be actuated pneumatically or hydraulically and DEAs are mainly used in the driving device of soft robots of biomimetic organisms. These elastomer actuators are an important way to drive soft robots; however, the existing driving speed, the generated driving force, and the difficulty of miniaturization of the prepared soft robots need to be further researched.

3.1.3 Others. In addition to the above-mentioned two types of common actuators, there are some other types of actuators. These actuators have been employed to study the functional characteristics of bionic natural organisms, mutual coupling of multiple actuators, realization of the miniaturization of actuators, *etc.*

Inspired by the osmotic function of plants, Must *et al.* designed a tendril-like soft robot based on an osmotic actuator by combining the principles of plant actuation and capacitive desalination. The designed soft robot is a reverse osmosis actuation strategy based on ion electro-sorption on a flexible porous carbon electrode driven by a low input voltage (1.3 V). Also, they demonstrated the reversible hardening ($\sim$5 times increase) and driving ($\sim$500-degree rotation) of a tension-like soft robot (diameter $\sim$1 mm). This driving strategy and the characteristics of being based on biocompatible materials and being able to be used under a safe voltage make the software robot in this work have strong application potential in the future.[204]

Cao *et al.* was inspired by inchworms to prepare an untethered soft robot. The body of this robot was composed of a dielectric elastomer actuator with driving deformation characteristics, and the two paper-based feet are composed of electroadhesive actuators. This soft robot could deform through alternate expansion/contraction of its body and realize movement through the adhesion/detachment of its two feet. Strong electroadhesion ensured stable movement, and the large voltage-induced deformation and fast response of the robotic body led to a velocity of 0.02 body length s^{-1}. This study also analyzed the body deformation of the soft robot by finite element analysis and proved that the soft robot is more susceptible to the influence of the dissipation process.[205]

To miniaturize prepared soft robots, Keya *et al.* used natural proteins as actuators and control systems to prepare molecular robots. The results showed that developing actuators with multiple embedded characteristics provides a feasible way to miniaturize robots, while retaining their complex and efficient functions.[206]

3.2 Materials-based driving strategies

Another way to drive soft robots is to use some of the unique characteristics of materials. The movement of soft robots can be generated through external environmental stimuli. The design and preparation of this type of soft robot mainly make improvements and breakthroughs from the aspect of applied materials. Also, the design and selection of materials for driving soft robots can be divided into two main categories. The first is to add particles that can respond to changes in the external environment to ordinary materials and drive the entire material system through the particles. The second is that the material itself has a good response to environmental conditions, and thus it can be actuated directly through changes in the environment. In this section, we mainly introduce elastomer and SRMs. Given that previous reviews rarely reviewed the SMMs applied in the field of soft robots, even if SMMs belong to SRMs to some extent, we still separately describe the articles on SMMs in recent years.

3.2.1 Elastomer-based driving strategy. Due to their reversible nature, elastomers are one of the most widely used materials to prepare soft robotics. Elastomers themselves do not have the characteristics of being driven in response to external environmental conditions, where functional particles that response to the environment in the elastomer are usually added to drive of whole soft material system under special conditions. They are represented by silicone rubber, which is mainly introduced in this section. Silicone rubbers are the most popular choice due to their easy fabrication process, low toxicity, and excellent mechanical properties, and silicone rubber material is a basic material with good comprehensive performances.[207,208] In some representative studies, the addition of functional particles to the elastomer was used to realize the characteristics of responding to the external environment to fabricate the gripper, which can be applied in the fields of machinery, sensing, *etc.*

The research on elastomers that respond to an external magnetic field and electric field is as follows. Venkiteswaran *et al.* combined silicone rubber and magnetic power to prepare various types of soft robotic grippers (tail gripper, flower gripper, and millipede robot) that can actuate in response to an external magnetic field.[209] Choi *et al.* proposed a gripper skin with reversible and variable hardness properties, which was based on shape-adaptive magnetorheological elastomers. The gripper skin was attached to a robot gripper and the SMRE composite consisted of silicon oil, silicone rubber, and carbonyl iron particles (CIPs) (Fig. 6a). They found that the CIP contents determined the mechanical property of the SMRE-based skin. The gripper with the SMRE-based skin could respond to a magnetic field to achieve the grasping and release of various types of target objects (a cylinder, cuboid, and triangular prism) easily without damaging the objects. When the applied magnetic field was 0 mT or 300 mT, the data graph of the grasping force measured when gripping objects of different shapes and the pictures of the weight of the real objects gripped are shown in Fig. 6b.[210] Nasab *et al.*[211] and He *et al.*[212] fabricated rigid tunable elastomer strips and soft tubular actuators, respectively, which could both respond to an electrical current. The rigid tunable strips were fabricated using a conductive propylene-based elastomer and used as the ligaments. The stiffness of the ligament changed under an electrical current. The soft tubular actuator fabricated using the liquid crystal elastomer exhibited multi-directional bending and large homogenous contraction (~40%) under an electric field. These characteristics caused it to respond to a current to achieve actuation.

In addition to the above-mentioned common elastomers, some novel elastomer materials and interesting functions have been proposed. Zhou *et al.* fabricated a novel soft robotic using a memory foam sheet and a patterned elastomeric layer to pick up various objects.[213] UV-curable elastomers were also used to prepare novel soft robots to achieve actuators. Thrasher *et al.* used elastomer photoresins *via* digital light processing additive manufacturing (DLP-AM) to fabricate a functional multi-material three-armed pneumatic gripper. The fabricated multi-material gripper with different stiffness between different materials could enhance the activation and bending movement of the gripper.[214] Patel *et al.* used a similar method to fabricate a soft actuator using a stretchable UV elastomer resin. Compared with silicone rubber that is not UV curable and commercially available UV curable elastomers, the highly stretchable and UV curable (SUV) elastomer they proposed could be stretched by up to 1100% (more than 5 times the elongation at break of the commercial UV curable elastomers) and be used as a gripper with outstanding performance for grasping objects (Fig. 6c). This SUV elastomer material could be used as a conductive bucky ball for electric switches as well. The picture and finite element simulation of an LED light when the soft robot was under pressure are shown in Fig. 6d. The preparation method and SUV elastomer system proposed in this work will play an important role in the fields of flexible electronic devices, soft robots, and acoustic metamaterials.[215] Some soft robots with self-healing property have attracted attention from researchers. Based on the so-called self-healing property, objects can recover completely from macroscopic damage over time. Roels *et al.* used thermal-reversible Diels-Alder (DA) chemistry to prepare a soft gripper with self-healing property (Fig. 6e). The 3D printed fingers were restored when they were damaged to varying degrees (fatal and not fatal), and the results showed that the injured fingers could repair themselves with only a small visual scar (Fig. 6f). The use of FFF 3D technology provides an idea for the similar preparation of soft robots in the future, enabling the prepared soft robots to exhibit more freedom and less manual effort. Also, the prepared soft robot with self-healing performance has important application prospect in some fields.[138]

In summary, in this section, we introduced the response of adding various functional nanoparticles to elastomers to achieve a response under magnetic and electrical conditions. In addition, the method of preparing elastomers by UV curing and soft robots with special feature of self-healing were also introduced. These techniques for preparing multifunctional soft robots using elastomers need to be used and improved in future research.

3.2.2 Stimuli-responsive material-based driving strategy. SRMs refer to the realization of perceivable and responsive materials to the external environment through the coordination of various functions in the materials, and there are usually many types of these materials.[216–218] Kim *et al.* reviewed the SRMs used for soft robots from the perspective of different types of materials (including carbon nanomaterials, metal nanomaterials, shape memory polymers, liquid crystal polymers and elastomers, azo-benzene, hydrogels, and bio-hybrids).[55] Ube *et al.* reviewed photo mobile materials with crosslinked liquid-crystalline structures, which have great potential application value in microactuators

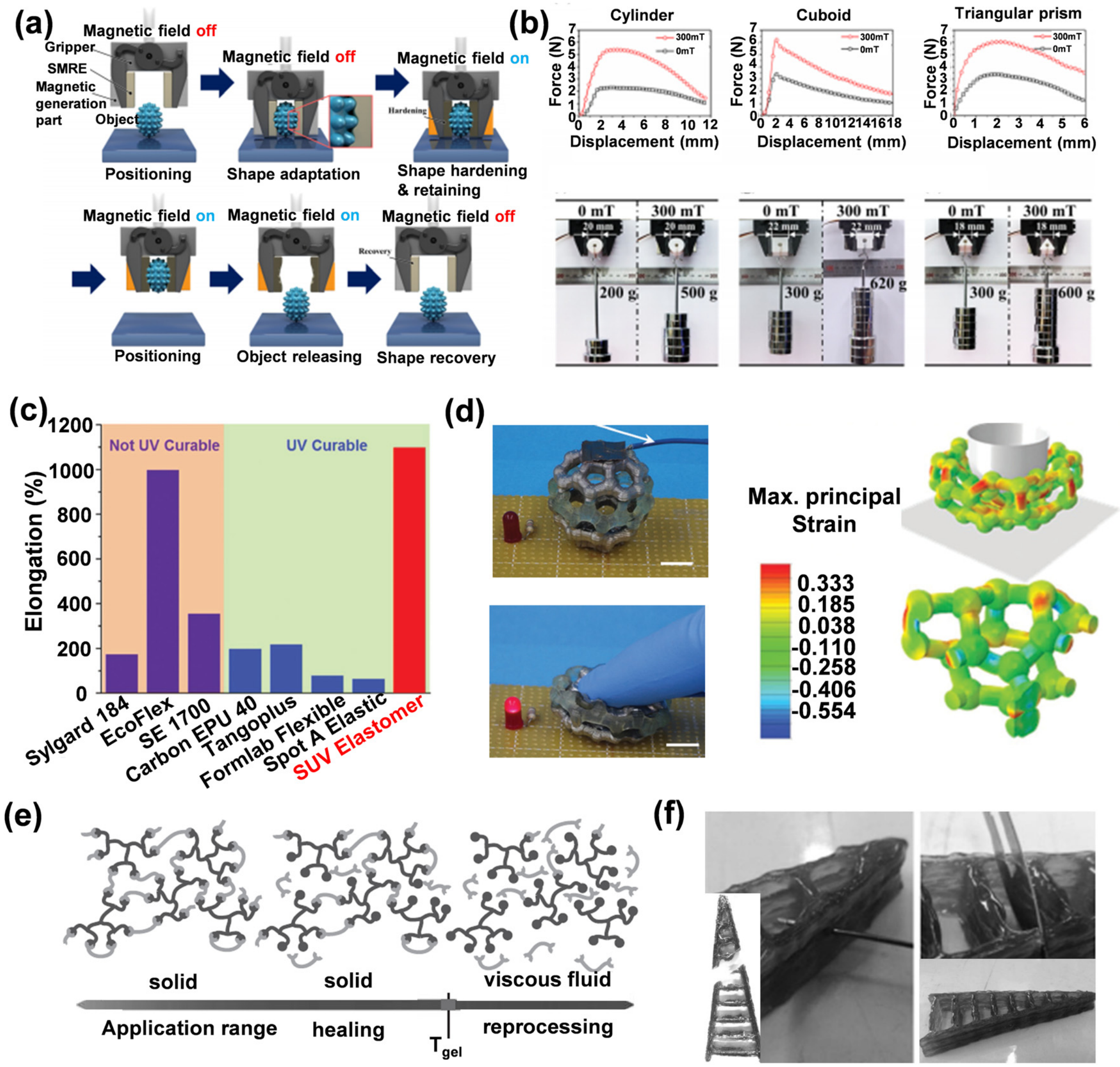


Fig. 6 (a) Operation scene of parallel jaw gripper with SMRE-based skin. (b) Data graph and schematic diagrams of grasping force for grasping objects with different shapes.[210] Copyright 2020, the American Chemical Society. (c) Elongation data graph of different elastomers. (d) Soft robot was used as a conductive bucky ball to light up an LED picture and the finite element simulation diagram when the conductive bucky ball was under pressure.[215] Copyright 2017, WILEY-VCH. (e) Schematic diagram of the prepared self-healing software material reversibly cross-linked through a DA bond. (f) Pictures of the damaged soft robot and after recovery.[138] Copyright 2019, Mary Ann Liebert, Inc.

and microfluidic devices.[219] In this section, we mainly review some representative articles published recently from the classification of response to different conditions (thermal, chemical, electronic, magnetic, *etc.*).

In the research on the response of soft robotics to the external thermal environment, the lower critical solution temperature (LCST) is an important concept. To realize the driving of materials through the control of the temperature to reach the LCST, poly(*N*-isopropylacrylamide) (pNIPAM) is usually used as the base material to achieve a good response to external temperature changes.[220,221] To achieve the functional applications of soft robot systems or enhance the mechanical characteristics of the materials, pNIPAM is usually combined with some other elements or materials. Breger *et al.*[222] and Ongaro *et al.*[223] used poly[*N*-isopropylacrylamide-*co*-acrylic acid] [*p*-NIPAM-AAc] as the main material and adjusted and controlled it by adding magnetic-responsive Fe_2O_3 to achieve a soft robotic system that responds to both thermal and magnetic changes. In addition to the research on PNIPAM-AAc as the main material to achieve a thermal and magnetic response, Kobayashi *et al.* combined the high swelling poly(oligoethylene glycol methyl ether methacrylate) (P(OEGMA-DSDMA)) and low swelling poly(acrylamide-*N*,*N*′-bis(acryloyl)cystamine) (P(AAm-BAC)) with magnetic Fe_2O_3 NPs to fabricate a soft gripper that can be used in stimuli-responsive biodegradable soft-gripping robots (Fig. 7a). The soft gripper moved under the action of a magnetic field and realized the grasping and release of soft cargo under the action of thermal changes, and the whole process is shown in Fig. 7b. In addition, the prepared soft gripper is based on the comparison of ISO standards, and the results showed that the gripper is simultaneously biocompatible and biodegradable. This experiment successfully proved that the soft grippers can be used for

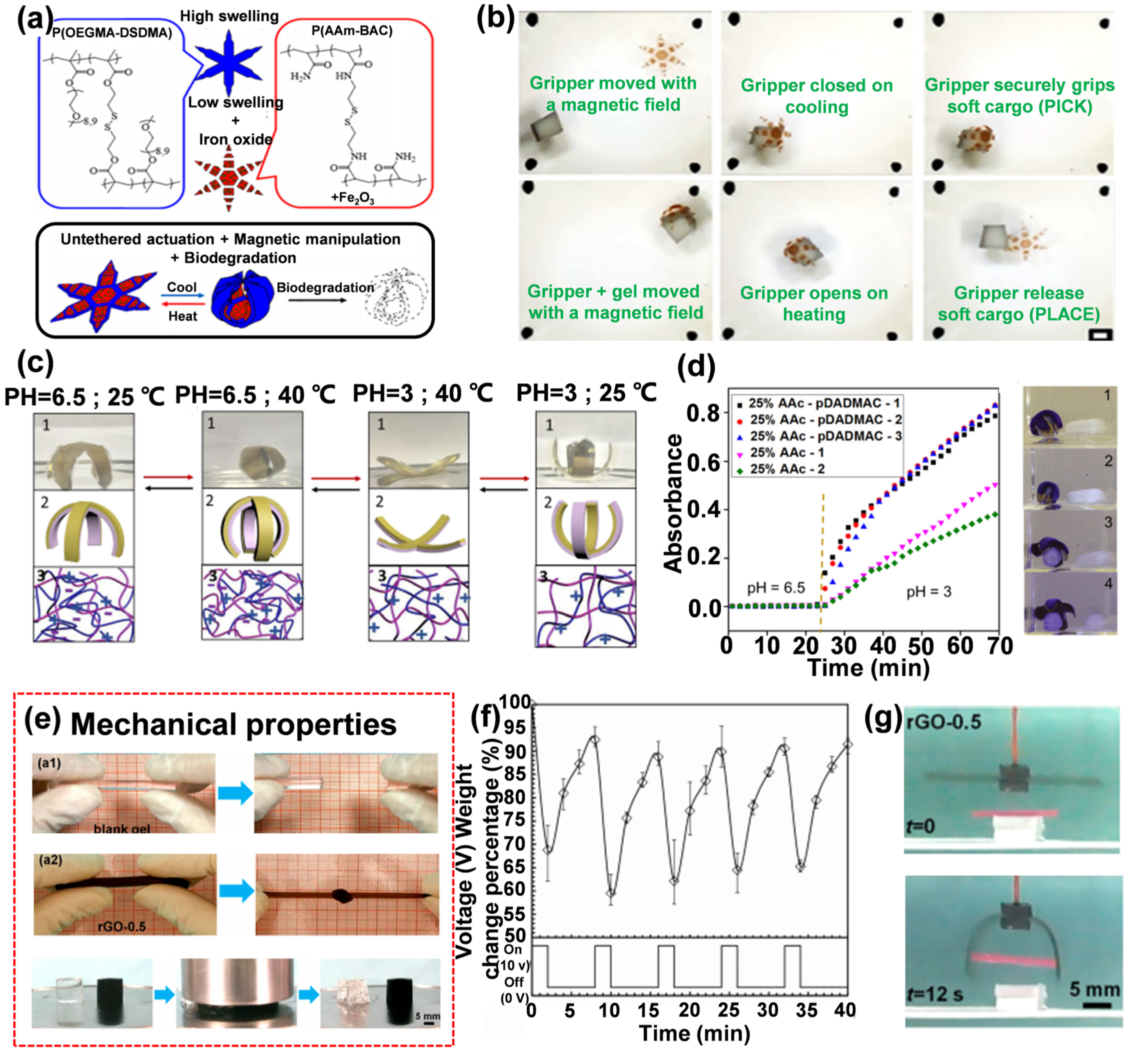


Fig. 7 (a) Schematic diagram of the molecular composition and structure of the materials used for the preparation of the soft robot and the prepared soft gripper operation process. (b) Whole process of soft cargo grasping and releasing by the soft gripper under the action of a thermal field and magnetic field.[224] Copyright 2018, the American Chemical Society. (c) Process of the soft gripper grasping and releasing under the action of pH and temperature. (d) Release profiles and pictures of soft robot triggered by pH.[228] Copyright 2017, The Royal Society of Chemistry. (e) Mechanical properties of the hydrogels. (f) Reversible deswelling/swelling behaviors of rGO-0.5 hydrogel. (g) Response of the soft robot to an electric field.[231] Copyright 2017, the American Chemical Society.

thermally actuatable drug patch applications. They also fabricated a range of thermally responsive self-folding structures using poly[oligo(ethylene glycol) methyl ether methacrylate] (POEGMA) gels, which could be used as a gripper to respond to three different temperatures.[224]

Driving materials through chemical stimulation has important potential in the preparation of soft robotics. The chemical stimulus includes pH, salt concentration, and solvent exposure.[225,226] At present, there is a multitude of research on the response to pH. Duan *et al.* fabricated a bilayer hydrogel with excellent mechanical properties to respond to pH. They used this pH-trigger swelling/deswelling smart material to prepare a soft robot that can load an object in 0.1 M HCl aqueous solution.[227] Li *et al.* combined a pNIPAm-based hydrogel and a layer of gold-coated PDMS to fabricate a smart material with a response to temperature and pH (Fig. 7c). When the smart material contained the positively charged polyelectrolyte poly(diallyldimethylammonium chloride) (pDADMAC) on the surface of PDMS, it could respond to temperature well. Thus, it was employed to fabricate a gripper that can grasp objects at low temperature (10 °C) and release objects at high temperature (50 °C). However, in the case of the PDMS surface without pDADMAC, the smart material could respond to pH, and the fabricated gripper swelled at pH 6.5 and deswelled at pH 3.0. The release profiles of the bilayers triggered by pH and a physical schematic diagram of the grabbing and releasing are shown in Fig. 7d.[228] In a similar study, Cheng *et al.* used two layers of hydrogels (pNIPAM and poly(2-(dimethylamino) ethyl methacrylate)) to fabricate a soft robot with fluorescence property, which could respond to both temperature and pH.[229] In addition, Justus *et al.* synthesized a soft robot that combined engineered bacteria, a flexible light-emitting diode (LED) circuit and soft pneu-net actuators to achieve autonomous parsing chemical signals through integrated organic and inorganic interfaces.[230]

Other SRM materials used to prepare soft robotic can respond to electric simulation. Yang *et al.* used a graphene oxide/poly(2-acrylamido-2-methylpropanesulfonic acid-*co*-acrylamide) (rGO/poly-(AMPS-*co*-AAm)) nanocomposite hydrogel to fabricate a soft actuator. By comparing the blank gel with rGO-0.2, rGO-0.5 and rGO-1.0, the prepared hydrogel with added rGO possessed excellent mechanical properties (Fig. 7e). The fracture stress and tensile fracture strain increased with an increase in rGO content. The fracture stress value of rGO-1.0 was about 4 times that of the blank gel, and the tensile fracture strain of rGO-1.0 reached 297.93%. When an electric field was applied for 2 min, the hydrogel shrank by 58–68% of its original state. After the electric field was removed, the hydrogel could swell again by immersing it in water for 6 min. The prepared hydrogel also exhibited a rapid and reversible electro-response (Fig. 7f). The gripper prepared with the rGO-0.5 hydrogel could grasp a15 mm object efficiently (Fig. 7g).[231] Chen *et al.* embedded super-aligned carbon nanotube sheets in PDMS to fabricate a soft robot that can respond to very low-driving direct current voltages to generate remarkable bending actuation than the existing thermal actuators.[232] Davidson *et al.* combined dielectric elastomers with fast and highly efficient actuation characteristics and liquid crystal elastomers with directed shape programmability property to fabricate actuators through a top-down photoalignment method. One of the highlights of this work is the possibility to program molecular alignment and localized large elastic anisotropy in liquid crystal elastomers. The linearly driven liquid crystal elastomer achieved a strain rate of more than 120% per second and an energy conversion efficiency of 20% when moving a load of more than 700 times the weight of the elastomer.[233] Also, in an early study, Zhou *et al.* prepared three types of grippers based on polymer MEMS that respond to ion movement in an electric field, thermal change, and electrochemical oxidation-reduction (redox) reaction, respectively. All three micro grippers could be used underwater with large deflections and required a low power input. This work is of great significance for the design of grippers that respond to various environmental factors underwater.[234]

Soft robots that respond to a magnetic field mainly contain additive magnetic responsive particles to achieve magnetic field control. The common magnetic field-responsive particles include Fe_2O_3, Fe_3O_4, ferrite powder, NdFeB, and NdPrFeB.[235–237] Ji *et al.* used digital light processing (DLP) 3D printing technology to fabricate a magnetic-responsive soft robot with magnetic photosensitive resin-incorporated Fe_3O_4 NPs. DLP 3D printing enables the fabrication of printed soft robots with complex architectures and excellent mechanical properties to achieve bending, deformation, and cargo transformation.[236]

There is also interesting research on hydrogels. Yuk *et al.* used hydrogels to fabricate a soft robot with six bending actuators to catch live fish in water. The soft robot exhibited high speed, high force, and was optically and sonically camouflaged in water. Soft robots with excellent mechanical properties can maintain their robustness and functionality when subjected to moderate stress.[238] Li *et al.* reported an interesting work on the fabrication of a soft robot that could walk in water on either flat or inclined surfaces and deliver objects through light and magnetic field-driven shape changes. The used and designed materials were rigidly embedded and macroscopically aligned ferromagnetic nanowires, which responded to a magnetic field in a soft photoactive hydrogel that responds to light. Through the theoretical description of the dual-response external energy input and experimental verification of the trajectory of the hydrogel, their work realized the programming and design of a soft robot to achieve a response to light and a magnet as expected.[239] The research conducted by Zhang *et al.* also suggested that the conversion of light into mechanical work is possible. They prepared chromatic actuators that respond to selected wavelength ranges by using nanotubes with different chiral distributions and based on polymer/single-walled carbon nanotube bilayers.[240] In addition, Zuo *et al.* constructed a multi-stimuli-responsive liquid crystal elastomer actuator that responds to three wavelength bands of light (520, 808, and 980 nm), which has broad application prospect in soft robots and bionic technology.[241]

In addition to the above-mentioned response, there is also research on photo-thermal,[242–244] humidity-light,[245] *etc.* responses. In summary, in the research on soft robots that achieve actuate responses to external conditions, the innovation of SRMs plays an important role in preparing soft robotics. These innovations include the improvement of materials themselves (such as adding functional particles and changing the ratio of materials used), and the coupling of multiple functional materials for preparation.

3.2.3 Shape memory material-based driving strategy. Shape memory materials (SMMs) usually exhibit changes in stiffness *via* phase transformations, enabling them to control their stiffness by controlling their phase, which have great potential in the preparation of soft robotics.[246–248] The representative shape memory materials are SMPs and SMAs.

There is some research on the application of soft robots for grippers using SMPs. Ge *et al.* used 3D technology to print a multi-material gripper with a length of a few mm that could grasp a screw.[158] Behl *et al.* fabricated a gripper in a cross-like manner by using PPD-PCL (75) ribbons. The gripper achieved grasping and release through temperature changes, and successfully grasped a penny.[249] At present, the main limitation of these systems is that their inherent softness leads to a small actuation force. Thus, to enable the better use of SMPs in grippers and grasping of relatively large and various objects, it is necessary to improve the mechanical properties of SMPs, such as employing SMP composites with other functional materials.

SMPs have also made some progress in the research of responding to thermal, light, magnetic, *etc.* changes. Therefore, these SMPs can be employed to prepare soft robots that respond to the external environment. Hubbard *et al.* converted SPM planer sheets into 3D objects with a controlled curvature. The sheet surface ink pattern could absorb infrared (IR) light to achieve localized heating. The driving of the materials could be reached when the temperature increased by the absorption of IR was higher than the activation temperature. The prepared soft robot could grab objects around 925 times its own weight and has a certain application prospect for temperature-controlled grabbing.[240] Ze *et al.* used two types of magnetic particles (NdFeB and Fe_3O_4) in an amorphous SMP matrix to fabricate a soft robot that can respond to a magnetic field (Fig. 8a). Low-coercivity particles made the matrix system soft through magnetic induction and high-remanence particles, which have reprogrammable magnetization profiles, induced a shape change when exposed to a magnetic field. The soft robot integrated reprogrammable, untethered, fast, and reversible shape transformation and shape locking into one system, thus providing a wide range of applications in many fields.[250] Chen *et al.* fabricated a novel soft robot using an SMP, which could respond to light and was magnetic repeatable and sensitive (Fig. 8b). The material of the soft robot was based on biocompatible PCL/TPU/Fe_3O_4@PDA, which exhibited a self-healing performance under light illumination (in 120 s) with the efficiency reaching 90%.[251] Recently, Liu *et al.* applied semicrystalline poly(ethylene-*co*-vinyl acetate) (EVA) together with silver nanowires (AgNWs) to assemble a complex 3D structure, multifunctional, and self-healing composite actuator by light welding. The AgNW/EVA composite could respond quickly under light irradiation and exhibited good reusability characteristics. The strategy of incorporating photo-thermal responsive composite particles in SMPs to achieve a response to light in this experiment provided inspiration for the preparation of soft robots that respond to special conditions. Also, the excellent self-healing function displayed by the soft robot in this experiment provides a good direction for the future design of soft actuators for use in the exploration, medical rehabilitation, and military reconnaissance fields.[252] Pang *et al.* designed a linear liquid crystal copolymer, in which the eutectic mesogens of azobenzene and phenyl benzoate self-organized into a smectic B phase. The fabricated liquid crystal copolymer combined the shape memory effect and photochemical phase transition to realize light-driven contraction as large as 81%.[253] In addition, Shiblee *et al.* used 3D printing technology to fabricate two layers of SMG materials (SMG 90-SA 10 and SMG 70-SA 30), which could be used as a soft robot. The soft

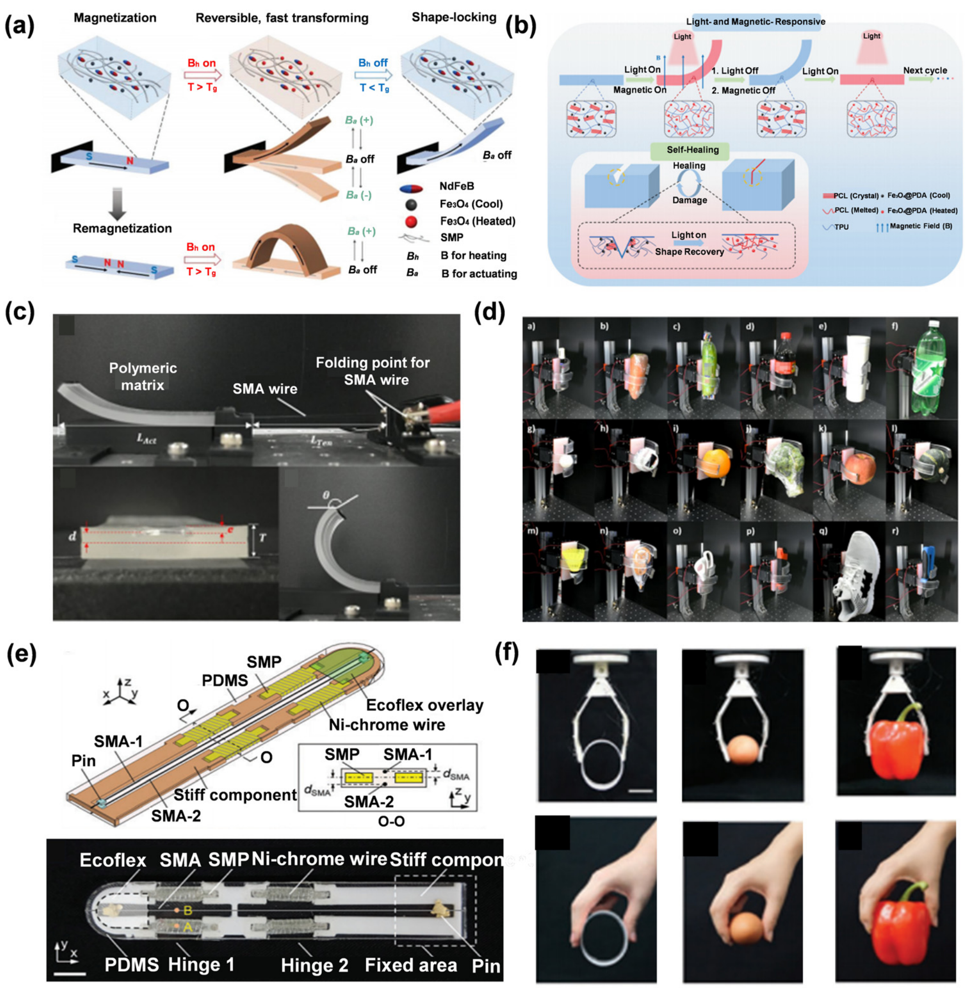


Fig. 8 (a) Working machine of magnetic SMP.[250] Copyright 2019, WILEY-VCH. (b) Schematic diagram of light- and magnetic-responsive actuation and shape memory assisted self-healing.[251] Copyright 2021, The Royal Society of Chemistry. (c) SMA actuator and the bending deformation. (d) Schematic diagram of SMA grasping various objects.[252] Copyright 2019, Springer Nature. (e) Schematic diagram of the soft finger assembly structure and its top view of the structure. (f) Schematic diagram of the prepared soft gripper imitating a human hand gripping objects (low to high stiffness).[257] Copyright 2017, Mary Ann Liebert, Inc.

robot could respond to temperature sensitively and achieved accurate gripping, transportation, and release of a glass vial upon swelling underwater.[113]

In SMA-based soft robotics, SMA wire embedded in the polymeric matrix is commonly used; however, method may cause a small stroke in the soft robot system, resulting in poor performances such as small bending angle and force compared to other types of soft robots. Thus, to solve this phenomenon, Lee *et al.* used free-slide SMA wires as tendons for soft actuation, and they decoupled the length of the matrix and the length of the SMA wires, while also allowing the compact packaging of the driving SMA wires to increase the bending angle and bending force (Fig. 8c). They applied the actuator to prepare a gripper, which could grasp a large range of objects weighing up to 1.5 kg, and the maximum pulling force of the prepared gripper could reach to 30 N (Fig. 8d). The proposed tendon design significantly improved the performances of SMA-based grippers.[254] The performance of SAM-based actuators mainly depends on the configuration of their cross-section. Rodriguez *et al.* fabricated an actuator with SMA wires by double casting. They confirmed that with the same cross-section configuration, the curved actuator has a larger maximum bending angle than a straight one. They used an SMA-based actuator to make two types of soft robotic grippers, where between the two, the curved gripper could lift an object with a weight of more than 3 times that by the straight gripper.[255]

There is also some research on imitating finger grabbing, Simone *et al.* fabricated a biomimetic prosthetic soft robot to imitate the structure of the human hand. To achieve multi-functional control and relatively fast rotation of the finger joints, they integrated an SMA wire in the protagonist-antagonistic muscle pair configuration.[256] Wang *et al.* fabricated a soft robot composed of three identical fingers with variable stiffness using SMA wires (Fig. 8e). To achieve multiple postures, each finger had two hinges, which could selectively change the stiffness of the hinges and actuate SMA wires. The prepared soft robot could adaptively grasp in the low stiffness state and hold in the high stiffness state efficiently (Fig. 8f). Due to the stiffness changeable mechanism, the maximum grasping force of the soft robot increased to around 10 times.[257]

In addition to SMA wire, She *et al.* developed a manipulator whose finger was composed of SMA strips and silicone rubber structure to grasp various objects and the gripper showed good adaptability and flexibility.[258] SMAs can be driven by a low voltage; however, high currents are required and the efficiency of SMAs is relatively low.

In this chapter, we mainly introduce the soft robot driving strategies based on either actuator or materials (Table 3). We introduce the actuator-based driving strategies and various common types of actuators used in the soft robotic field. Also, the characteristics of different types of actuators and some related research published in recent years are described. Material-based driving strategies are introduced, with indirect-driven materials (elastomer) and directly-driven materials (SRMs and SMMs) respectively. Unlike other related reviews, in this part of the introduction, we analyze the different response conditions. This chapter has important implications for the design of varying driving modes in soft robots in the future.

4. Applications

Due to the characteristics of their soft bodies, more degrees of freedom and the ability to be designed to respond to the external environment according to the functional requirements, soft robots have vast potential applications ranging from industry to the medical field. In this chapter, we introduce the combination of soft robots with artificial intelligence, as well as the application of soft robots in the medical and industrial fields.

4.1 Artificial intelligence

As one of the current hot topics, artificial intelligence is being connected with many areas of life. The connection of artificial intelligence and robot design is an innovation in the field of robotics. In this section, we explore the roles of artificial

Table 3 The advantages and disadvantages of driving strategies of soft robots

Driven strategies of soft robots		Advantages	Disadvantages
Actuator-based driving strategies	Soft pneumatic actuators (SPAs)	Convenient preparation, easy operation, robustness, reusability, and controllability.	SPA usually require numerous pneumatic accessories, which are difficult to miniaturize.
	Fluidic elastomer	FEAs can achieve extending, contracting, bending, and twisting with low-pressure fluid.	The fluid contained in the channel is pressurized to generate stress and local strain in the elastomer materials.
	Actuators (FEAs)	Softness, light weight, large stroke and can exhibit large strain (10–50%) and moderate stress (∼100 kPa).	DEAs will be affected by high temperature to a certain extent, and when the designed electric signal system interaction and control are complex, the measurement accuracy will be reduced.
Material-based driving strategies	Dielectric elastomeric actuators (DEAs)	Easy fabrication process, low toxicity, and excellent mechanical properties.	Relies on the addition of nanoparticles to achieve driving.
	Elastomer	Can be directly driven by environmental factors.	The speed of the response needs to be improved, and the driving force generated is not very large.
	Stimuli-Response Materials (SRMs)	Stiffness changes *via* phase transformations to achieve direct drive.	SMA wire embedded in the polymer matrix may cause a small stroke, resulting in a poor performance.

intelligence in the preparation of soft robots and the functional applications of combining soft robots with artificial intelligence.

The introduction of machine learning is useful for the perception, design, and prediction of some characteristics of soft robotics. Initially, Nakajima *et al.* believed that the various dynamics of driving soft materials can be efficiently used for machine learning. They used a soft silicone arm to confirm this and the results showed that the method fits into a general perspective of computation and exploits the properties of physical materials in the real world.[259] At present, the combination of soft robots and machine learning is mainly reflected in the output of certain signals (such as strain, stress, pressure, temperature, and chemical) through soft robots as the input parameters of machine learning, combined with machine learning algorithms (such as support vector machine (SVM), logistic regression, dimensional reduction, and gradient boosting) to realize the modeling of unknown soft actuate systems and human-robot interaction. Therefore, effective parameter input and efficient algorithm selection play an essential role to achieve the combination of soft robots and machine learning (Fig. 9a). With the development of current technology, the collection of soft robot signals mainly comes from electronic skin or soft devices with sensing equipment. Shin *et al.* reviewed electronic skins and machine learning for the fabrication of intelligent soft robots.[260] In addition to the research mentioned in their review, there are also some other studies. Thuruthel *et al.* embedded a redundant and unstructured soft sensor topology in a soft actuator and used a recurrent neural network (RNN) to achieve the perception of soft robotics. They chose long short-term memory (LSTM) to train the sample data, which was from a vision-based motion capture system, due to the ease in training LSTM networks for long time-lag tasks. The trajectory of the fingertip (blue line) and the predicted positions (red line) are shown in Fig. 9b. Regarding the force prediction of the fingertip, the prediction and error plots

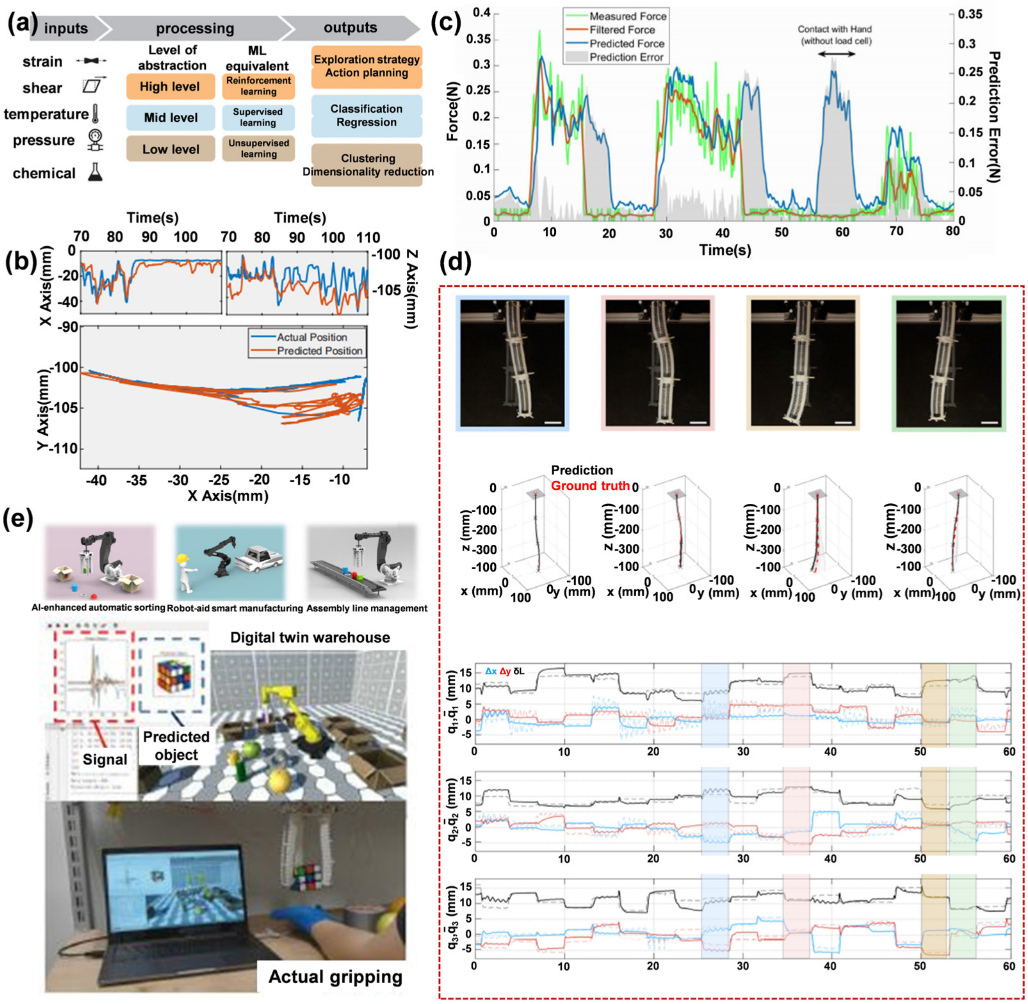


Fig. 9 (a) Machine learning technology used to process raw sensory information, different levels of abstraction to help robot perception and action planning.[259] Copyright 2018, John Wiley and Sons. (b) Predicted motions of the fingertips with cPDMS sensors. (c) Force prediction at the fingertip.[261] Copyright 2019, The American Association for the Advancement of Science. (d) Validation results on random arm actuation.[263] Copyright 2020, IEEE. (e) Schematic diagram of digital twin applications of things sensory system and the system interface integrated with object recognition and its digital twin warehouse application.[265] Copyright 2020, Springer Nature.

of the same test are shown in Fig. 9c. This system exhibited a delay in detecting the cessation of contact, and the average error in other cases was around 0.05 ± 0.06 N. The method in this work enabled the development of force and deformation models for soft robotic systems.[261] Preechayasomboon *et al.* used actuating fluid as a sensing medium to fabricate a hybrid sensor with high-fidelity proprioception property. Through the signals given by the sensor, they used RNN to derive the poses of the actuator. Experiments showed that this method is feasible for realizing proprioception and is robust to common sensor failures.[262]

There is similar research using soft robotic skin to contact the outside and the collected signals are combined with RNN for analysis. Truby *et al.* used deep learning to build a framework for predicting the 3D configuration of a soft robot from the feedback of soft and proprioceptive sensor skin. They introduced a kirigami-enabled strategy to fabricate soft sensors from off-the-shelf sheets of electrically conductive silicone. The prepared soft arm was divided into three segments (S1, S2, and S3) and the trained RNN well-predicted the steady-state configuration of the prepared soft arm even with hysteretic, non-monotonic feedback from the piezoresistive sensors. The validation results of the random arm actuation are shown in Fig. 9d. The photographs of the soft arms with four different kirigami sensors, ground truth and predicted configurations of the soft arm poses, and ground truth and predicted configuration parameters *versus* time for three segments of the arms during random actuation cycles are shown from top to bottom, respectively. This work provides a fundamental step toward the use of deep learning in the 3D configuration of soft robotics, while the closed-loop feedback control system provided lays a good foundation for the subsequent 3D configuration research and control design of other soft robots.[263] Weerakoon *et al.* used trained RNN (LSTM) to estimate the degree of curvature of a soft robot through strain signals in a dynamic control framework. The strain signals were received from the soft robotic skin, which was a spray-coated piezoresistive sensing layer on a latex membrane. They designed an adaptive controller to track the desired degree of curvature trajectory, and both low-frequency and high-frequency target trajectories could achieve satisfactory curvature tracking.[264] Accordingly, information theory and machine learning will play a huge role in enabling soft robots to achieve human-like performance levels.

There is interesting research that combines popular digital twins with soft robotics to achieve the combination of virtual and reality. Jin *et al.* reported a smart soft robotic gripper that could capture continuous motion and tactile information through the triboelectric nanogenerator sensors of the gripper. The outstanding part of this work is that the soft gripper achieved human machine interaction efficiently. The information collected by the triboelectric sensor on the objects grasped by the soft robotic gripper was further processed through support vector machine algorithm, and thus the computer could identify the grasped objects with a high accuracy rate of 98.1% (Fig. 9e). Combining this research with the field of digital twins has realized the replication of real-time operation in the virtual environment, therefore creating a perfect virtual assembly line and unmanned warehouse.[265]

In summary, one of the major difficulties of controlling soft robotic systems is the stochastic and nonlinear dynamics. The combination of machine learning and soft robotics can encode dynamic behavior and nonlinearity, and hopefully solve the problem of hysteresis and nonstationary behavior. However, this emerging technology also has some problems to be solved and improved, such as the model bias, overfitting, increasing system complexity, validation, and reproducibility.[266] The combination of soft robotics with other artificial intelligence fields has also shown excellent results. Thus, this will become a trend for soft robotics to become more intelligent in the future.

4.2 Medical

Soft robotics have great potential application prospects in the medical field due to their compliance and mechanical properties. The degrees of freedom, biomimicry and biocompatibility are important factors for the application of soft robots in the medical field.[267]

In terms of the soft robotics used in medical field, to ensure the stable and normal operation of the whole system, the materials should be compatible with the human or animal body and tissues to a certain extent. Currently, the materials used in the medical field mainly include flexible fluidic actuators (FFAs),[268–270] SMMs,[271–273] electroactive polymers (EAPs),[274,275] hydrogels,[276,277] and conditional response materials.[278–280] Utilizing the deformation characteristics of these materials in a specific environment and transforming them make them have important application value in the biomedical field. The soft robotics made of these materials have certain application prospects in surgery,[280] drug delivery,[281] diagnosis of various diseases and conditions,[282] rehabilitation,[283] and treatment in certain medical conditions.[284] Cianchetti *et al.* comprehensively reviewed the application of soft robots in the biomedical field, including the application of soft tools in the various directions mentioned above in biomedical research, traditional and novel soft materials and different actuation strategies. They also discussed the approaches and applications in the biomedical field in the future.[285] In addition, it is important for soft robots to effectively heal wounds and not cause any damage to the surrounding soft tissue in these processes, which is also one of the difficult problems that needs to be solved.[286–288] Regarding the preparation technology of soft robots used in medical applications, in addition to the common methods introduced in the second chapter, 4D printing technology exhibits real-time direction and transmit real-time important information, which is of great significance for the application of soft robots in the medical field. Hann *et al.* reviewed the technical approaches for 4D printing, smart materials used for 4D technology and the vision of 4D soft robots in biomedical engineering.[289]

There are also some soft robots related to bionics. Soft robots are designed, manufactured, and applied in the medical field through inspiration from the functional characteristics of organisms. For example, the soft robots with a bionic octopus, where Wang *et al.* developed a cable-driven soft robot surgical system for single-port minimally invasive surgery on a beating heart, which is improved the accuracy of the operation (Fig. 10a). However, the large size of the soft robot manipulator made the operation limited during the surgery process, which

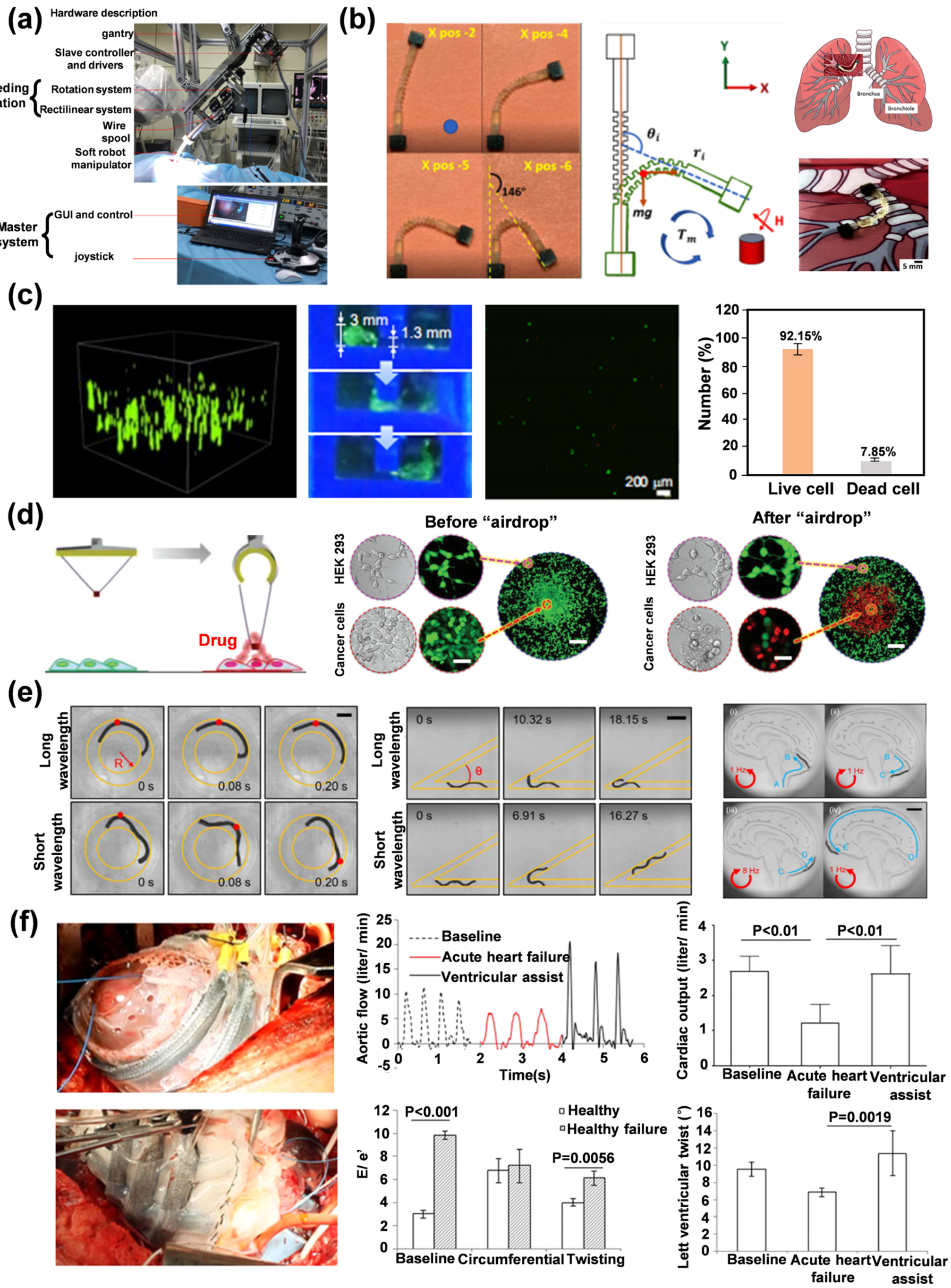


Fig. 10 (a) Overview of the soft robot surgical system.[290] Copyright 2016, Springer. (b) Example of the turning locomotion of the soft robot inspired by inchworms, displacement of the front legs on the *x*, *y* axis and corresponding deflection angle, as well as schematic diagram of the motion in the human lung.[281] Copyright 2020, Elsevier. (c) DNA robot as a vehicle for cell delivery. The pictures from left to right represent the multi-layered cells cultured in DNA robot under a fluorescence microscope, the DNA robot passes through a narrow channel with living cells, the fluorescence images of the cells released from the DNA robot, and the live and dead cell quantitative analysis.[292] Copyright 2020, John Wiley and Sons. (d) Schematic diagram of the work of the soft robot for drug delivery and enlarged views of cancer cells (A549) and unaffected cells (HEK293) before and after the "airdrop" of the drug bomb.[278] Copyright 2019, John Wiley and Sons. (e) Experimental maneuverability of the sheet-shaped soft robot performing wave crawling mode and the sheet-shaped robot manipulated in a phantom that simulates the brain aqueduct by adjusting the magnetic rotation frequency.[279] Copyright 2021, Publisher. (f) Demonstration and test data graph of applying soft robotic equipment to a porcine model of acute heart failure.[294] Copyright 2017, The American Association for the Advancement of Science.

will be improved in future research.[290,291] Joyee *et al.* fabricated a multi-material soft robot inspired by inchworms. The soft robot had a magnetic particle-polymer composite body, which was fabricated *via* 3D printing technology. This soft robot can be used in the drug delivery field due to the fact that its reservoir can store liquid drug and it can release the drug once it reaches the target (Fig. 10c).[281] Also inspired by worms, Tang *et al.* fabricated a DNA robot based on a super-soft and super-elastic magnetic hydrogel. The DNA robot exhibited shear-thinning, cyclic strain, and biocompatibility. This robot could complete a series of complex magnetically-driven movements and successfully worked as a vehicle to deliver cells in confined space by virtue of its 3D porous networked structure. A schematic diagram of the soft robot during turning locomotion and drug delivery in the human lungs is shown in Fig. 10c.[292] Xu *et al.* fabricated a tissue-engineered transformable soft robot inspired by swimming whales, which could be actuated by a muscular tail fin. The soft robot exhibited unprecedented controllability and responsiveness, and it could be applied as a cargo carrier for the programmed delivery of chemotherapeutic agents to selectively eradicate cancer cells (Fig. 10d).[278]

In a recent study, Lindenroth *et al.* fabricated a fluidic soft robot comprised of six embedded fluid actuators to translate and rotate needles as well as adapt stiffness in the coupling between the needles and ear canal. They developed a vision system for tracking and positioning, thereby achieving safe needle insertion and reducing the movement of the needle. The soft robot was successfully for intratympanic steroid injection.[284] The above-mentioned situation is attributed to the movement of the soft robot in a non-confined space. The application of soft robotics in the medical field sometimes affects the motion of the robot due to the fluid-filled confined spaces in the body. Ren *et al.* broke through the motion of the previously prepared soft robots, which were only suitable for dry environment.[293] They proposed sheet-shaped soft millirobots that can achieve multimodal locomotion (rolling, undulatory crawling, undulatory swimming, and helical surface crawling) in different fluid-filled confined environments. Neodymium–iron–boron (NdFeB) microparticles tended to align the soft robot directions along an external magnetic field to achieve the deformation of the soft robot. Applying different external magnetic field caused different deformation modes to adapt to different environments. Thus, the prepared soft robot is expected to be applied in confined spaces filled with fluid in the human body in the future (Fig. 10e).[279] Some of the above-mentioned research prepared soft robots with certain application prospects in the medical field, but there are also related research that applies the prepared soft robots in practice. Roche *et al.* prepared a soft robotic device with material properties and structure like the mature heart. This soft robot could support the cardiac output of a failing pig heart. The practical experiments proved that six pigs suffered from heart failure through drug treatment, making their heart failure by 45% of its basic level. After applying the soft robotic device, the heart function recovered to 97% of the pre-medicine treatment (Fig. 10f).[294]

In summary, in this chapter on the application of soft robots in the medical field, we introduce some previous reviews in this field. Then, we described some examples of the application of bionic soft robots in the medical field in detail, which will inspire researchers to some extent. Finally, we reviewed some recent high-quality related articles. In short, the application of soft robots in the medical field is currently in the research stage, and further exploration and research are needed for them to be applied in real life in the future.

4.3 Sensors

Sensors are devices that measure a physical quantity (such as pressure, speed, temperature, sound, ad light) and convert it into an electronic signal. The combination of specific sensors and soft robotics can realize the signal output of specific physical characteristics, which makes soft robots have great application potential in many fields. Wang *et al.* summarized the development of soft robots with mechanical sensing and provided a comprehensive understanding of this field. They specifically introduced the developments in all aspects of sensing including proprioception, tactile sensing, sensing morphology, and sensor configuration.[295] In this chapter, we mainly introduce sensor design and the recent research progress.

The design structure and the selected material will directly affect the role of the sensor in soft robots. Also, tactile sensors are a key challenge in the development of soft robots due to their limited flexibility and deformability. Thus, to solve the poor flexibility of the sensors used in soft robotics, the use of conductive thermoplastic elastomers (CTPEs) plays an essential role. CTPEs are a thermoplastic elastic matrix homogeneously mixed with carbon black powder under high pressure and temperature. Integrating CTPEs in the software part of robots will not change the overall mechanical performance of the system. The excellent extension characteristics of CTPEs enable them to fully extend in the soft part without causing damage to the sensor.[296,297] Compared with strain gauges,[298] ionic liquid sensors,[299,300] ZnO nanowire films,[301] graphene foam[302] and silver nanocomposites,[303] CTPEs[297,304] have some excellent mechanical characteristics. Hughes *et al.* used functional CTPE materials as a strain sensor. They developed a theoretical framework to provide design principles for optimizing and characterizing the sensor implementation. A framework and schematic illustration of the soft tactile sensing of objects are shown in Fig. 11a. The construction of the theoretical framework has important guiding significance for the sensors of soft robotics to identify the specific parameters of target objects. They also applied the proposed theoretical framework to deformation sensing in soft robotic manipulators. Although the proposed approach needs to be improved in some aspects, such as identifying complex geometries of grasped objects and using less sensor elements to provide more grasped object deformation information, this research allows robots to identify grasped objects to enable an improved gripping and manipulation performance. Also, it has important reference significance for related follow-up research.[305] In terms of tactile sensors, Yang *et al.* proposed an embedded sensing solution, where they inserted a pair of optical fibers in the structural cavity of soft robotic fingers so that the optical fibers will not affect the adaptive performance of the fingers, and the prepared soft robotic fingers had the properties of exceptional adaptation in all directions.

The electrical signal output by the sensor has important meaning in the analysis of object characteristics. Comparing actual object properties with the sensor estimated properties, an object sorting task and identified sectional diameters of 94% objects within ±6 mm error and measured 80% of the structural strains within ±0.1 mm mm^{-1} error were observed, respectively (Fig. 11b). This research opens the door for scalable

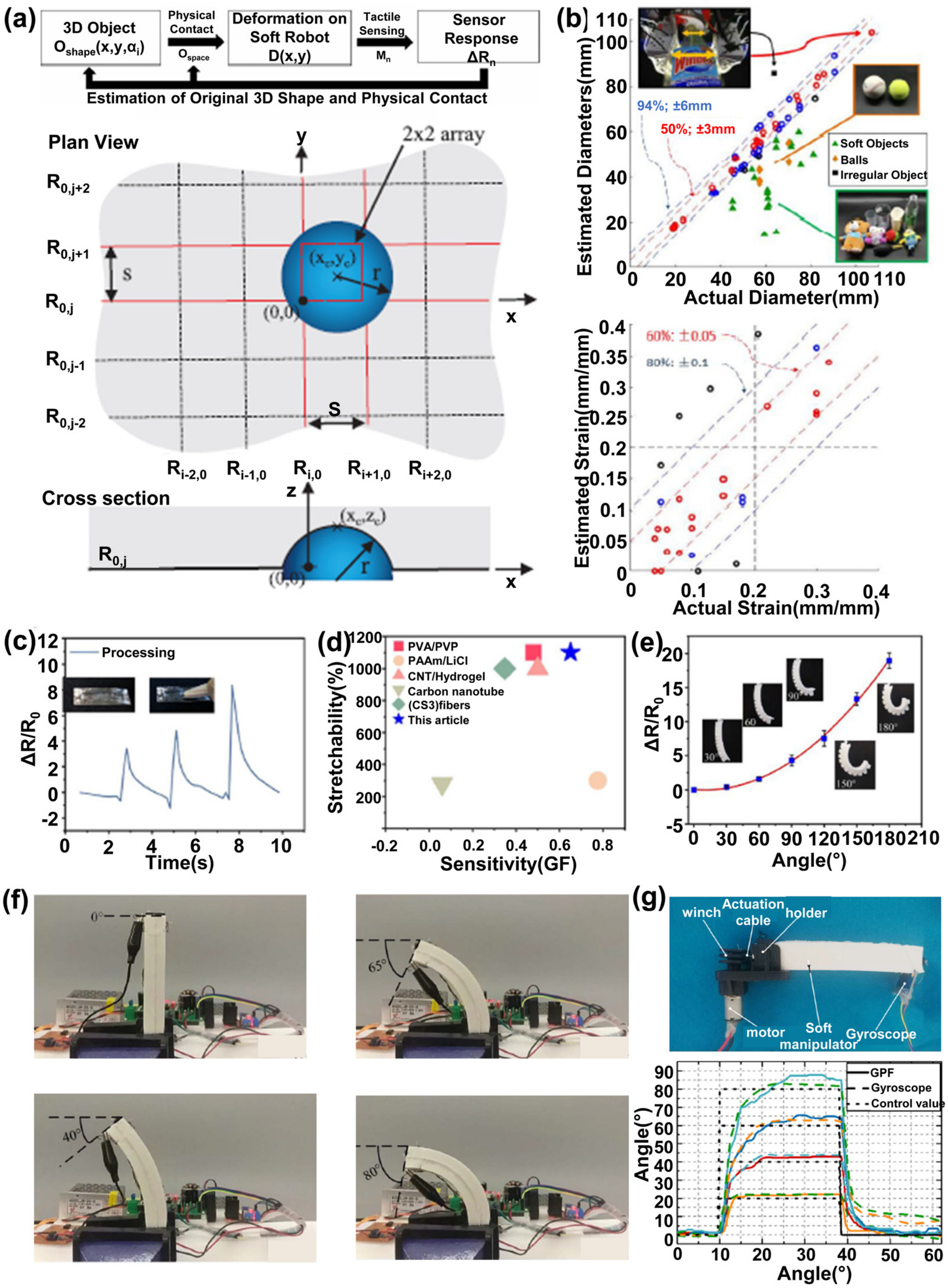


Fig. 11 (a) Framework and schematic illustration of soft tactile sensing of objects.[305] Copyright 2018, Mary Ann Liebert, Inc. (b) Comparison of actual object characteristics and sensor estimated characteristics.[306] Copyright 2020, IEEE. (c) Signals of hydrogel sensor responses to external force. (d) Performance of Wang's hydrogel sensor compared with similar research. (e) Hydrogel sensor relationship between the bending angle and the relatively resistance.[276] Copyright 2021, Elsevier. (f) Locomotion of the manipulator with sensor CPF. (g) Schematic diagram and the step responses of the soft manipulator.[308] Copyright 2018, IEEE.

and adaptive physical interactions in the unstructured environment of the soft robotic field.[306]

There are also sensors for measuring stretching and angles and estimating the stretching ratio and the bend angle by the electrical output signal. Hydrogels can respond to electronical and mechanical properties due to their controllability, and thus have potential for the fabrication of sensors. Gao *et al.* researched the mechanical properties of hydrogels based on a novel discrete element method (DEM) simulation. Both the experiment and simulation results indicated that the fracture property of the inhomogeneous hydrogels are superior to the homogenous hydrogels. The model in this work has potential for researching motion and mechanical response and has important significance for the application of hydrogel sensors used in soft robots.[307]

Recently, Wang *et al.* designed a highly stretchable hydrogel sensor with 1200% maximum tensile strain and only 0.0625% water loss within 30 days. The hydrogel sensor could monitor the soft finger bending, twisting, and external force efficiently compared with another similar study (Fig. 11c–e, respectively). The light-weight sensor had a negligible impact on the motion of soft fingers. Also, they found that strain sensitivity of the hydrogel sensor increased with the strain. This close-loop control made the entire soft robot system more intelligent, realizing human-robot interactions and control.[276] Tang *et al.* made a soft manipulator embedded with conductive nylon fiber. The conductive nylon fiber consisted of coiling conductive polymer fibers (CPFs) and the relation between the resistance change rate and the bending angle could be measured *via* the CPFs (in Fig. 11f and g).[308] In addition, there are also some sensors used to respond to thermal changes and combine with medical treatment.[309]

In summary, compared with the design of the soft robot structure, the selection and breakthrough of materials for soft robots play an important role in the field of sensors. The soft robots used for sensor function can collect signals, and combined with machine learning, can realize the learning and prediction of specific parameters.

4.4 Engineering

The flexible body and multiple degrees of freedom of soft robots allow them have application potential in engineering. In this section, we introduce the latest research process of some soft robots used in pipeline engineering and transportation engineering.

The soft robots used in pipes are special types of robots that can carry sensors and tools to move outside or inside. There is some related research on the application of soft robots in pipelines, such as wheeled robots,[310,311] legged robots,[312] spiral robots,[313,314] and peristaltic robots.[315] However, the previous design of soft robots has some problems, such as small locomotion speed, long actuation period, and low load capability. Thus, to overcome these limitations, Zhang *et al.* fabricated a novel parallel-pipe-crawling pneumatic soft robot consisting of three extensible pneumatic soft actuators and two flexible feet (Fig. 12a). They optimized the performance of the designed soft robotics through the process of structural design, finite element simulation, kinematic modeling, trajectory planning, prototype fabrication, and prototype experiments. Finally, the soft robot crawling experiments in different scenarios showed that the maximum load that it could withstand was 2.456 kg, the crawling speed was higher than 15 mm s^{-1}, and the minimum turning radius was 38.2 mm (Fig. 12b).[316]

Another category of soft robots used in pipelines is inspired by nature. These biomimetic soft robots achieve applications in pipeline inspection by combining inspiration from biological motion, such as snakes[317] and earthworms.[318,319] These bionic soft robots are commonly very flexible; however, the movement of bionic snake soft robots in the vertical direction is limited. Some soft robots with bionic earthworms have solved this problem. Schumacher *et al.* used a multi-casting-based fabrication method to create a multi-material multi-actuator soft robot inspired by earthworms, which could be used in a varying-slope (horizonal, vertical and oblique) transparent pipe.[73] Zhang *et al.* designed a soft robot inspired by earthworms, which could achieve sharp turns with large diameter changes in pipelines.[318] In addition, Zhang *et al.* fabricated a soft robot inspired by worms, which could be operated in various complicated tubular environments such as different pipeline diameters, dry and hard surfaces, water, oil, and gas environments. This robot could remove a load of more than 10 times its own weight, and the visualization unit, biopsy and electromagnetic sensors installed at the end of the robot could be used for real-time image inspection, operation, and robot tracking, respectively.[320] Xiao *et al.* prepared a bionic electrically driven soft robot named "Janus", which was composed of a uniaxial oriented liquid crystal network (LCN) strip, a laminated Kapton layer, and thin resistive wires embedded between them (Fig. 12c). Janus was easy to operate, could be reprogrammed, and be reversibly transformed in shape when in the electric power on and off states. Janus could crawl in a pipeline and be reprogrammed to adapt to different pipeline diameters. As shown in Fig. 12d, when the diameter of the pipeline changed from 9.3 mm to 3.8 mm, Janus could pass smoothly with a speed changed from 0.75 cm min^{-1} to 0.34 cm min^{-1}. Given that Janus is composed of a single piece of material and has two parts undergoing opposite deformations simultaneously under a uniform stimulation, this allowed it to walk like two human legs and move three different loads at different speeds (Fig. 12e). This research not only opens new horizons in the development of soft robots made of liquid crystal polymers, but also provides design ideas for the use of soft robots for pipeline crawling and transportation engineering.[321]

In terms of cargo transportation, Tang *et al.* fabricated an amphibious climbing soft robot (ACSR) by combining a proposed switchable adhesion actuator inspired by inchworms. The design of the actuator is to inflate air into the top spiral channel and deform it into a stable 3D dome shape to achieve negative pressure in its cavity (Fig. 12f). The ACSR could adapt to various surfaces such as dry, wet, slippery, smooth on ground and under water. The vertical climbing speed of ACSR could reach 286 mm min^{-1} (1.6 body length min^{-1}) and its weight could withstand over 200 g (over 5 times its weight) (Fig. 12g). The ACSR with switchable adhesion property has potential

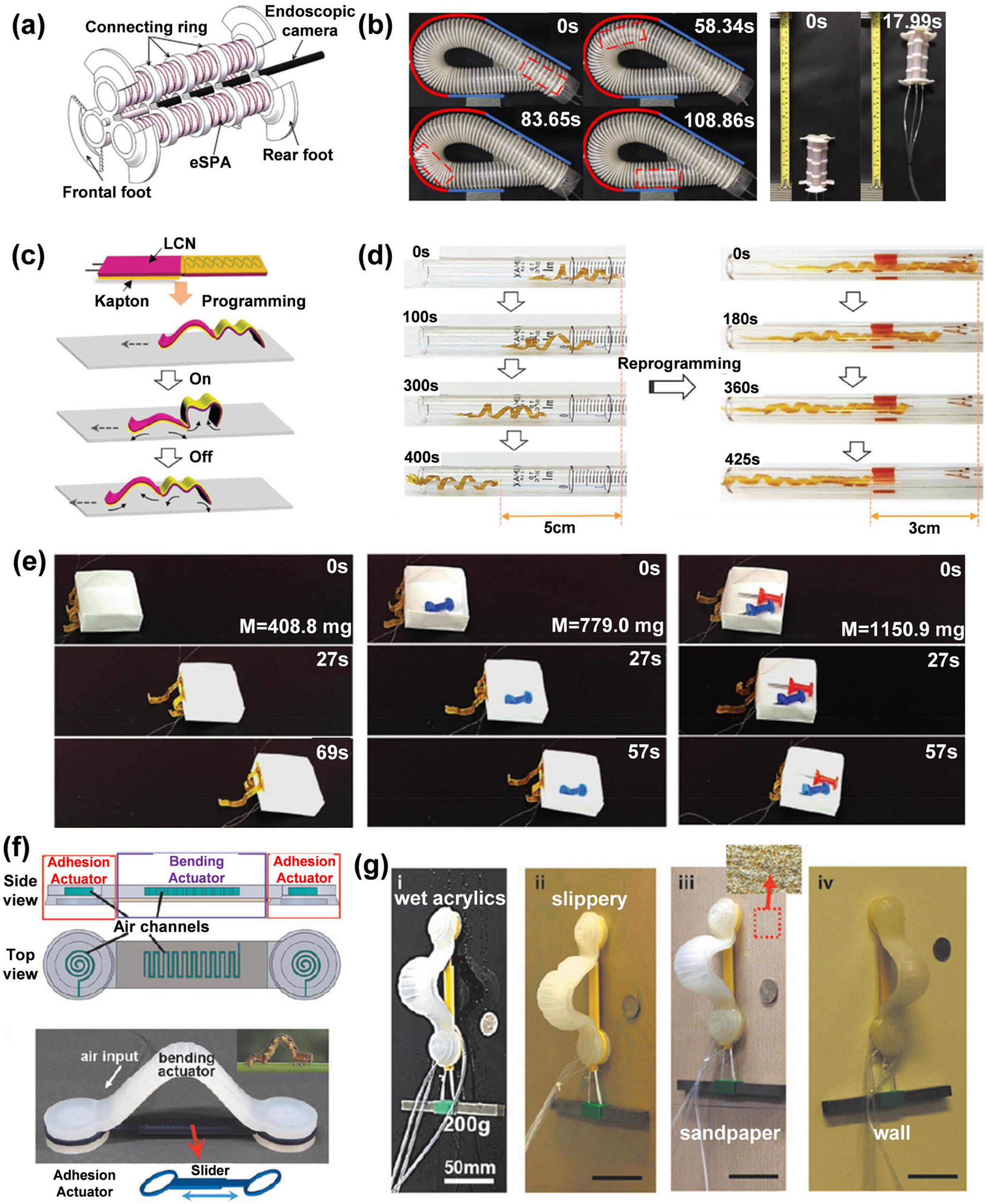


Fig. 12 (a) Design structure diagram of pipe crawling soft robot. (b) Photograph of soft robot crawling in a pipeline and crawling on a textured surface.[316] Copyright 2019, IEEE. (c) Schematic diagram of the Janus crawling principle. (d) Crawling pictures in different diameters helical pipelines through reprogrammed Janus. (e) Photographs showing the locomotion of Janus conveyor moving three different loads at different speeds.[317] Copyright 2019, John Wiley and Sons. (f) Schematic diagram of the design structure of a bionic worm crawling soft robot. (g) Bionic worm soft robot crawling with heavy object on various surfaces.[322] Copyright 2018, Mary Ann Liebert, Inc.

application prospects in object transportation.[322] Overall, this section mainly introduced the application of soft robots in pipeline engineering and transportation engineering. Soft robots can crawl in different pipeline diameters and various surface environments. Also, soft robots have certain transportation capacity and can transport goods up to several times their own weight.

In this chapter, we mainly introduced the applications of soft robots including artificial intelligence, medicine, sensors, and engineering. The development of these soft robots has broad application potential. However, they have limitations and rely on their response to the outside to realize the output of the function, which will make the prepared soft robots have a certain gap in practical application.

5. Conclusions and perspective

In this work, we comprehensively reviewed the recent advances in soft robotics with focus on the fabrication technologies, driving strategies, and applications of soft robots. The commonly used technologies for the fabrication of soft robots were divided into three types based on the detailed processing procedures, *i.e.*, top-down approaches (*e.g.*, molding, etching, laser and soft lithography), bottom-up approaches (*e.g.*, adding reinforcement and additive manufacturing solutions), and complex fabrication approaches. The widely used and emerging fabrication technologies in the above-mentioned three types were briefly introduced. The characteristics, advantages and limitations of the fabrication technologies were discussed, and the typical soft robots and/or materials that suit each fabrication technology were also reviewed. As the key part of soft robotics, the commonly used driving strategies were reviewed and summarized into two main types, *i.e.*, actuator-based and materials-based driving strategies, according to the driving mechanisms. Some representative and recent studies on soft robots based on different driving strategies and related aspects were reviewed, and the advantages and characteristics of different driving strategies were discussed and compared. In addition, the wide range of applications of soft robots in artificial intelligence, medicine, sensors, and engineering was briefly introduced, and we also provided an overview of emerging soft robots/materials with good performances and application potential in these areas.

Generally, soft robotics is an emerging field that is growing rapidly with the development of nanotechnology and new materials. Soft robots exhibit better performances in many aspects including infinite degrees of freedom, softness, flexibility, and biocompatibility compared to traditional robots. However, there are still some remaining challenges in fabrication and driving strategy of soft robots, which limit their development and widespread use. One important challenging issue is the fabrication technology of soft robots. As discussed in Section 2, most of the present fabrication technologies have limitations and can only be employed to produce one or a few types of soft robots. Universal fabrication technology that can produce different types of soft robots regardless of the materials and structure designs is a possible research direction in soft robotics and has attracted much attention from researchers. 4D printing is a typical emerging technology and is expected to play a key role in the development and fabrication of next-generation soft robots because it can be used to precisely fabricate soft robots with different structures and materials, as discussed in Section 2.3. However, the present 4D printing technology has relatively strict requirements for the ink materials, and the mechanical and stimuli-responsive properties of soft robots prepared by 4D printing need to be improved. Fundamental studies on the correlations between the properties of soft robots and technological details of 4D printing are urgently needed.

The driving strategy is the key part for soft robots to perform specific functions (*e.g.*, moving and deformation). Many previous soft robots are inspired by organisms in nature, and different actuators or/and stimuli-responsive materials are employed to achieve the desired functions. However, the performance of biomimetic soft robots is much less than that of real organisms due to the size limit and simple structure of actuators and stimuli-responsive materials. In the near future, the design of driving strategies can be greatly improved by using simulation and artificial intelligence technologies. The development of fabrication technologies and updated understanding of biological knowledge can also contribute to the fabrication of more delicate and multifunctional soft robots. The soft robotics prepared in the future will be comprehensively improved in sensing and proprioception, feedback and adaptive control, path planning, robot intelligence, *etc.* Additionally, the application area of soft robots will be rapidly extended to the environmental and biological fields. Soft robots have innate advantages in terms of bio- and environmental compatibility compared to traditional robots, and they are expected to play a key role in many areas including minimally invasive or non-invasive surgery/testing, smart drug delivery systems, artificial organs, water/air quality monitoring, and energy harvesting. New soft robots will be divided into many sub-classes and have improvement in specific properties such as degradability, mechanical properties, and sensitivity to meet the needs of different applications.

Soft robotics is an emerging research area, and there are many challenging issues to be solved. This work provided a comprehensive overview of the fabrication, driving strategy, and applications of soft robots and discussed the perspective of soft robotics, providing useful information for the development of a new generation of soft robots.

Conflicts of interest

We declare no conflict of interest in this paper.

Acknowledgements

This paper was supported by Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Research Chairs Program (H. Zeng), the National Natural Science Foundation of China (No. 51575528), the Science Foundation of China University of Petroleum, Beijing (No. 2462020XKJS01), Yunnan Province Science and Technology Major Project for Materials Genetic Engineering of Rare and Precious Metal (202002AB080001), U.S. National Science Foundation (Award No. 2004251). The authors (Xiaoxiao Dong, No. 202006440137; Li Yang, No. 201908530039) would like to acknowledge China Scholarship Council.

References

1 T. Brogårdh, *Annu. Rev. Control*, 2007, **31**, 69.
2 I. Nourbakhsh, R. Powers and S. Birchfield, *AI MAG*, 1995, **16**, 53.
3 R. F. Shepherd, F. Ilievski, W. Choi, S. A. Morin, A. A. Stokes, A. D. Mazzeo, X. Chen, M. Wang and G. M. Whitesides, *Proc. Natl. Acad. Sci. U. S. A.*, 2011, **108**, 20400.
4 D. Floreano and R. J. Wood, *Nature*, 2015, **521**, 460.
5 M. Balasingam, *Int. J. Clin. Pract.*, 2017, **71**, e12989.

6 Q. Wu, Y. Liu and C. Wu, *EURASIP J. Wirel. Commun. Netw.*, 2018, 20.
7 N. Kashiri, A. Abate, S. J. Abram, A. Albu-Schaffer, P. J. Clary, M. Daley, S. Faraji, R. Furnemont, M. Garabini and H. Geyer, *Front. Robot. AI*, 2018, **5**, 129.
8 A. V. Le, V. Prabakaran, V. Sivanantham and R. E. Mohan, *Sensors*, 2018, **18**, 2585.
9 J. B. Song and K. S. Byun, *J. Mech. Sci. Technol.*, 2009, **23**, 2747.
10 M. Hussein, *Adv. Robot.*, 2015, **29**, 1575.
11 G. Zheng, Y. Zhou and M. Ju, *ISA Trans.*, 2020, **100**, 38.
12 E. A. Alandoli and T. S. Lee, *Robotica*, 2020, **38**, 2239.
13 M. R. Cutkosky and S. Kim, *Philos. Trans. R. Soc., A*, 2009, **367**, 1799.
14 G. Alici, *MRS Adv.*, 2018, **3**, 1557.
15 E. W. Hawkes, L. H. Blumenschein, J. D. Greer and A. M. Okamura, *Sci. Robot.*, 2017, **2**, eaan3028.
16 D. Rus and M. T. Tolley, *Nature*, 2015, **521**, 467.
17 D. Trivedi, C. D. Rahn, W. M. Kier and I. D. Walker, *Appl. Bionics Biomech.*, 2008, **5**, 99.
18 M. T. Tolley, R. F. Shepherd, B. Mosadegh, K. C. Galloway, M. Wehner, M. Karpelson, R. J. Wood and G. M. Whitesides, *Soft Robot.*, 2014, **1**, 213.
19 K. Chubb, D. Berry and T. Burke, *Bioinspir. Biomim.*, 2019, **14**, 063001.
20 J. B. Trimmer, *Curr. Biol.*, 2013, **23**, R639.
21 H. Kim, J. Choi, K. K. Kim, P. Won, S. Hong and S. H. Ko, *Nat. Commun.*, 2021, **12**, 4658.
22 A. A. Calderón, J. C. Ugalde, J. C. Zagal and N. O. Pérez-Arancibia, Design, fabrication and control of a multi-material-multi-actuator soft robot inspired by burrowing worms, *ROBIO*, Qingdao, China, Dec., 2016.
23 X. Wang, B. Yang, D. Tan, Q. Li, B. Song, Z. S. Wu, A. D. Campo, M. Kappl, Z. Wang, S. N. Gorb, S. Liu and L. Xue, *Mater. Today*, 2020, **35**, 42.
24 T. Umedachi, V. Vikas and B. A. Trimmer, *Bioinspir. Biomim.*, 2016, **11**, 025001.
25 A. D. Marchese, C. D. Onal and D. Rus, *Soft Robot.*, 2014, **1**, 75.
26 S. Wöhl and S. Schuster, *J. Exp. Biol.*, 2007, **210**, 311.
27 E. D. Tytell and G. V. Lauder, *J. Exp. Biol.*, 2002, **205**, 2591.
28 C. D. Onal and D. Rus, *Bioinspir. Biomim.*, 2013, **8**, 026003.
29 M. Cianchetti, M. Calisti, L. Margheri, M. Kuba and C. Laschi, *Bioinspir. Biomim.*, 2015, **10**, 035003.
30 B. Mazzolai, L. Margheri, M. Cianchetti, P. Dario and C. Laschi, *Bioinspir. Biomim.*, 2012, **7**, 025005.
31 K. Y. Su, J. Z. Gul and K. H. Choi, *Soft Robot.*, 2017, **4**, 224.
32 S. Wakimoto, K. Ogura, K. Suzumori and Y. Nishioka, *Adv. Robotics*, 2009, **25**, 1311.
33 M. Sugisaka and H. Zhao, *Artif. Life Robot.*, 2007, **11**, 223.
34 A. D. Marchese, K. Komorowski, C. D. Onal and D. Rus, Design and control of a soft and continuously deformable 2D robotic manipulation system, *ICRA*, Hong Kong, China, May, 2014.
35 R. F. Shepherd, A. A. Stokes, J. Freake, J. Barber, P. W. Snyder, A. D. Mazzeo, L. Cademartiri, S. A. Morin and G. M. Whitesides, *Angew. Chem., Int. Ed.*, 2013, **52**, 2892.
36 C. Cheng, J. Cheng and W. Huang, *IEEE Access*, 2019, **7**, 75073.
37 A. Firouzeh, M. Salerno and J. Paik, Soft pneumatic actuator with adjustable stiffness layers for Multi-Dof Actuation, *IROS*, Hamburg, Germany, Sept., 2015.
38 K. Liu, J. Wu, G. H. Paulino and H. J. Qi, *Sci. Rep.*, 2017, **7**, 3511.
39 A. Albu-Schaffer, O. Eiberger, M. Grebenstein, S. Haddadin, C. Ott, T. Wimbock, S. Wolf and G. Hirzinger, *IEEE Robot. Autom. Mag.*, 2008, **15**, 20.
40 R. J. Wood, S. Avadhanula, R. Sahai, E. Steltz and R. S. Fearing, *J. Mech. Des.*, 2008, **130**, 052304.
41 A. A. Schäffer, O. Eiberger, M. Grebenstein, S. Haddadin, C. Ott, T. Wimböck, S. Wolf and G. Hirzinger, *IEEE Robot. Autom. Mag.*, 2008, **15**, 20.
42 M. Jiang, Z. Zhou and N. Gravish, *Soft Robot.*, 2020, **7**, 770.
43 Z. Wang, K. Li, Q. He and S. Cai, *Adv. Mater.*, 2019, **31**, 1806849.
44 A. Stilli, H. A. Wurdemann and K. Althoefer, *Sci. Robot.*, 2017, **4**, 16.
45 H. Sareen, U. Umapathi, P. Shin, Y. Kakehi, J. Ou and H. Ishii, P. Maes, Printflatables: printing human-scale, functional and dynamic inflatable objects, *CHI*, Denver, USA, May, 2017.
46 A. Firouzeh, Y. Sun, H. Lee and J. Paik, Sensor and actuator integrated low-profile robotic origami, IROS, Tokyo, Japan, Nov., 2013.
47 C. D. Onal, R. J. Wood and D. Rus, *IEEE ASME Trans. Mechatron.*, 2012, **18**, 430.
48 Y. Yang, K. Vella and D. P. Holmes, *Sci. Robot.*, 2021, **6**, 6426.
49 G. Gu, J. Zhu, L. Zhu and X. Zhu, *Bioinspir. Biomim.*, 2017, **12**, 011003.
50 M. B. Trimmer, P. R. H. Ewoldt, M. Kovac, H. Lipson, N. Lu, M. Shahinpoor and C. Majidi, *Soft Robot.*, 2014, **1**, 63.
51 J. Zhang and E. Diller, *Soft Robot.*, 2018, **5**, 761.
52 A. Raatz, S. Blankemeyer, G. Runge, C. Bruns and G. Borchert, *Soft Robot.*, 2015, 173.
53 M. Calisti, G. Picardi and C. Laschi, *J. R. Soc., Interface*, 2017, **14**, 20170101.
54 M. Bächer, E. Knoop and C. Schumacher, *Curr. Robot. Rep.*, 2021, **2**, 211.
55 H. Kim, S. k Ahn, D. M. Mackie, J. Kwon, S. H. Kim, C. Choi, Y. H. Moon, H. B. Lee and S. H. Ko, *Mater. Today*, 2020, **41**, 243.
56 N. Elango and A. Faudzi, *Int. J. Adv. Manuf. Technol.*, 2015, **80**, 1027.
57 Y. Lee, W. Song and J. Y. Sun, *Mater. Today Phys.*, 2020, **15**, 100258.
58 H. Son and C. Yoon, *Actuators*, 2020, **9**, 115.
59 N. Gariya and P. Kumar, *Mater. Today: Proc.*, 2021, **46**, 11177.
60 K. J. Cho, J. S. Koh, S. Kim, W. S. Chu, Y. Hong and S. H. Ahn, *Int. J. Precis. Eng. Manuf.*, 2009, **10**, 171.

61 Y. Yang, Y. Li and Y. Chen, *Bio-Des. Manuf.*, 2018, **1**, 14.
62 F. Schmitt, O. Piccin, L. Barbé and B. Bayle, *Front. Robot. AI*, 2018, **5**, 84.
63 A. Zolfagharian, A. Kaynak and A. Kouzani, *Mater. Des.*, 2020, **188**, 108411.
64 S. Zaidi, M. Maselli, C. Laschi and M. Cianchetti, *Curr. Robot. Rep.*, 2021, **2**, 355.
65 M. A. Mousa, M. Soliman, M. A. Saleh and A. G. Radwan, *IEEE Access*, 2020, **8**, 184524.
66 A. Menciassi, S. Gorini, G. Pernorio, L. Weiting, F. Valvo and P. Dario, Design, fabrication and performances of a biomimetic robotic earthworm, *ROBIO*, Shenyang, China, Aug., 2004.
67 Z. Shen, J. Na and Z. Wang, *IEEE Robot. Autom. Lett.*, 2017, **2**, 2217.
68 A. D. Mazzeo and D. E. Hardt, *J. Micro. Nanomanuf.*, 2013, **1**, 021001.
69 W. D. Brouwer, E. Van Herpt and M. Labordus, *Composites, Part A*, 2003, **34**, 551.
70 C. Wang, K. Sim, J. Chen, H. Kim, Z. Rao, Y. Li, W. Chen, J. Song, R. Verduzco and C. Yu, *Adv. Mater.*, 2018, **30**, 1870087.
71 H. Lipson, *Soft Robot.*, 2014, **1**, 21.
72 R. K. Katzschmann, A. D. Marchese and D. Rus, *Soft Robot.*, 2015, **2**, 155.
73 C. M. Schumacher, M. Loepfe, R. Fuhrer, R. N. Grass and W. J. Stark, *RSC Adv.*, 2014, **4**, 16039.
74 M. A. Bell, K. P. Becker and R. J. Wood, *Adv. Mater. Technol.*, 2021, **7**, 2100605.
75 J. Tapia, E. Knoop, M. Mutný, M. A. Otaduy and M. Bächer, *Soft Robot.*, 2020, **7**, 332.
76 G. Maloisel, E. Knoop, C. Schumacher and M. Bächer, *IEEE Trans. Robot.*, 2021, **37**, 996.
77 P. Polygerinos, S. Lyne, Z. Wang, L. F. Nicolini, B. Mosadegh, G. M. Whitesides and C. J. Walsh, Towards a Soft Pneumatic Glove for Hand Rehabilitation, *IROS*, Tokyo, Japan, Nov., 2013.
78 H. Zhao, Y. Li, A. Elsamadisi and R. Shepherd, *Extreme Mech. Lett.*, 2015, **3**, 89.
79 S. Kriegman, A. M. Nasab, D. Shah, H. Steele, G. Branin, M. Levin, J. Bongard and R. Kramer-Bottiglio, Scalable sim-to-real transfer of soft robot designs, *RoboSoft*, New Haven, USA, Jul., 2020.
80 J. Germann, B. Schubert and D. Floreano, Stretchable Electroadhesion for Soft Robots, *IROS*, Chicago, USA, Sept., 2014.
81 C. D. Onal and D. Rus, A Modular Approach to Soft Robots, *BIOROB*, Rome, Italy, Jun., 2012.
82 R. V. Martinez, J. L. Branch, C. R. Fish, L. Jin, R. F. Shepherd, R. M. Nunes, Z. Suo and G. M. Whitesides, *Adv. Mater.*, 2013, **25**, 205.
83 Q. Wang, Z. Wu, J. Huang, Z. Du, Y. Yue, D. Chen, D. Li and B. Su, *Composites, Part B*, 2021, **223**, 109116.
84 H. Niu, R. Feng, Y. Xie, B. Jiang, Y. Sheng, Y. Yu, H. Baoyin and X. Zeng, *Soft Robot.*, 2021, **8**, 507.
85 J. Zhang, A. Jackson, N. Mentzer and R. Kramer, *Front. Robot. AI*, 2017, **4**, 46.
86 D. Mijatovic, J. C. Eijkel and A. Van den Berg, *Lab Chip*, 2005, **5**, 492.
87 R. P. Chang, C. Chang and S. Darack, *J. Vac. Sci. Technol., A*, 1982, **20**, 45.
88 B. L. Zambrano, A. F. Renz, T. Ruff, S. Lienemann, K. Tybrandt, J. Vörös and J. Lee, *Adv. Healthcare Mater.*, 2021, **10**, 2001397.
89 V. M. Donnelly and A. Kornblit, *J. Vac. Sci. Technol., A*, 2013, **31**, 050825.
90 X. Sun, L. Zhuang, W. Zhang and S. Y. Chou, *J. Vac. Sci. Technol., B*, 1998, **16**, 3922.
91 N. Farrow, L. McIntire and N. Correll, Functionalized textiles for interactive soft robotics, *ICRA*, Singapore, Singapore, May, 2017.
92 Y. Jiang, Y. Wang, H. Wu, Y. Wang, R. Zhang, H. Olin and Y. Yang, *Nano-Micro Lett.*, 2019, **11**, 99.
93 G. B. Blanchet, Y. L. Loo, J. A. Rogers, F. Gao and C. R. Fincher, *Appl. Phys. Lett.*, 2003, **82**, 463.
94 B. S. Shin, J. G. Kim, W. S. Chang and K. H. Whang, *Int. J. Precis. Eng. Manuf.*, 2006, **7**, 56.
95 H. Deng, K. Sattari, Y. Xie, P. Liao, Z. Yan and J. Lin, *Nat. Commun.*, 2020, **11**, 1.
96 Y. Xia and G. M. Whitesides, *Angew. Chem., Int. Ed.*, 1998, **37**, 550.
97 K. E. Paul, M. Prentiss and G. M. Whitesides, *Adv. Funct. Mater.*, 2003, **4**, 13.
98 M. Tyagi, J. Pan and E. W. H. Jager, *Microsyst. Nanoeng.*, 2019, **5**, 44.
99 A. Vergara, Y. S. Lau, R. F. Mendoza-Garcia and J. C. Zagal, *PLoS One*, 2017, **12**, e0169179.
100 F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen and G. M. Whitesides, *Angew. Chem., Int. Ed.*, 2011, **50**, 1890.
101 S. A. Morin, R. F. Shepherd, S. W. Kwok, A. A. Stokes, A. Nemiroski and G. M. Whitesides, *Science*, 2012, **337**, 828.
102 B. Mosadegh, P. Polygerinos, C. Keplinger, S. Wennstedt, R. F. Shepherd, U. Gupta, J. Shim, K. Bertoldi, C. J. Walsh and G. M. Whitesides, *Adv. Funct. Mater.*, 2014, **24**, 2163.
103 W. Oropallo and L. A. Piegl, *Eng. Comput.*, 2016, **32**, 135.
104 J. Y. Lee, J. An and C. K. Chua, *Appl. Mater. Today*, 2017, **7**, 120.
105 H. N. Chia and B. M. Wu, *J. Med. Biol. Eng*, 2015, **9**, 1.
106 N. Shahrubudin, T. C. Lee and R. Ramlan, *Procedia Manuf.*, 2019, **35**, 1286.
107 T. Umedachi, V. Vikas and B. A. Trimmer, Highly deformable 3-D printed soft robot generating inching and crawling locomotions with variable friction legs, IROS, Tokyo, Japan, Nov., 2013.
108 O. D. Yirmibesoglu, J. Morrow, S. Walker, W. Gosrich and Y. Menguc, Direct 3D printing of silicone elastomer soft robots and their performance comparison with molded counterparts, *RoboSoft*, Livorno, Italy, Apr., 2018.
109 J. Wang, A. Goyanes, S. Gaisford and A. W. Basit, *Int. J. Pharm.*, 2016, **503**, 207.
110 Z. K. Shao and Y. L. Jiang, *J. Mech. Electr. Eng.*, 2015, **32**, 180.

111 V. Chan, J. H. Jeong, P. Bajaj, M. Collens, T. Saif, H. Kong and R. Bashir, *Lab Chip*, 2012, **12**, 88.
112 B. N. Peele, T. J. Wallin, H. Zhao and R. F. Shepherd, *Bioinspir. Biomim.*, 2015, **10**, 055003.
113 M. N. I. Shiblee, K. Ahmed, M. Kawakami and H. Furukawa, *Adv. Mater. Technol.*, 2019, **4**, 1900071.
114 T. Wallin, J. Pikul, S. Bodkhe, B. Peele, B. Mac Murray, D. Therriault, B. McEnerney, R. Dillon, E. Giannelis and R. Shepherd, *J. Mater. Chem. B*, 2017, **5**, 6249.
115 E. B. Joyee and Y. Pan, *Procedia Manuf.*, 2019, **34**, 566.
116 E. B. Joyee, A. Szmelter, D. Eddington and Y. Pan, *Soft Robot.*, 2020, **9**, 1.
117 S. Kumar, *JOM*, 2003, **55**, 43.
118 A. Mazzoli, *Med. Biol. Eng. Comput.*, 2013, **51**, 245.
119 P. Bertrand, F. Bayle, C. Combe, P. Goeuriot and I. Smurov, *Appl. Surf. Sci.*, 2007, **254**, 989.
120 H. Wu, O. Wang, Y. Tian, M. Wang, B. Su, C. Yan, K. Zhou and Y. Shi, *ACS Appl. Mater. Interfaces*, 2021, **13**, 12679.
121 Y. S. Krieger, S. Schiele, S. Detzel, C. Dietz and T. C. Lueth, Shape memory structures-automated design of monolithic soft robot structures with pre-defined end poses, *IEEE ICRA*, Montreal, Canada, May, 2019.
122 A. Rost and S. Schdle, The SLS-generated Soft Robotic Hand – An Integrated Approach using Additive Manufacturing and Reinforcement Learning, *ICMLA*, Miami, USA, Dec., 2013.
123 D. B. Roppenecker, A. Pfaff, J. A. Coy and T. C. Lueth, Multi Arm Snake-Like Robot Kinematics, *IROS*, Tokyo, JAPAN, Nov, 2013.
124 S. Wei, L. Zhang, C. Li, S. Tao, B. Ding, S. Xia and H. Zhu, *J. Mater. Chem. C*, 2019, **7**, 6786.
125 J. G. Cham, S. A. Bailey, J. E. Clark, R. J. Full and M. R. Cutkosky, *Int. J. Robot. Res.*, 2002, **21**, 869.
126 J. G. Cham, S. A. Bailey, J. E. Clark, R. J. Full and M. R. Cutkosky, Fast and Robust: Hexapedal Robots via Shape Deposition Manufacturing, *ISER*, Waikiki, USA, Dec, 2000.
127 S. Kim, M. Spenko, S. Trujillo, B. Heyneman and M. R. Cutkosky, Whole body adhesion: Hierarchical, directional and distributed control of adhesive forces for a climbing robot, *IEEE ICRA*, Rome, Italy, Apr., 2007.
128 J. Gafford, Y. Ding, A. Harris, T. McKenna, P. Polygerinos, D. Holland, C. Walsh and A. Moser, *J. Mech. Robot.*, 2015, **7**, SI021006.
129 A. M. Dollar and R. D. Howe, *Adv. Robot.*, 2005, **19**, 523.
130 K. S. Boparai, R. Singh and H. Singh, *Rapid Prototyp. J.*, 2016, **22**, 281.
131 A. Georgopoulou, T. Sebastian and F. Clemens, *Flex. Print. Electron.*, 2020, **5**, 035002.
132 A. Dijkshoorn, M. Schouten, S. Stramigioli and G. Krijnen, *Sensors*, 2021, **21**, 3710.
133 R. Mutlu, E. Sariyildiz, T. Nozaki and G. Alici, Design of A Multi-stage Stiffness Enhancing Unit for a Soft Robotic Finger and its Robust Motion Control, *IECON*, Washington, DC, The United States, Oct., 2018.
134 H. K. Yap, H. Y. Ng and C. H. Yeow, *Soft Robot.*, 2016, **3**, 144.
135 J. E. M. Teoh, R. C. Mysa, T. V. Truong and P. V. Y. Alvarado, Propulsive performance of an undulating fin soft robot, *MTS/IEEE Oceans 2020: Singapore-U.S. Gulf Coast*, Online, Oct., 2020.
136 M. Jiang, Z. Zhou and N. Gravish, *Soft Robot.*, 2020, **7**, 770.
137 J. Carrell, G. Gruss and E. Gomez, *Rapid Prototyping. J.*, 2020, **26**, 855.
138 E. Roels, S. Terryn, J. Brancart, R. Verhelle, G. Van Assche and B. Vanderborght, *Soft Robot.*, 2020, **7**, 711.
139 H. M. Anver, R. Mutlu and G. Alici, 3D Printing of a Thin-Wall Soft and Monolithic Gripper Using Fused Filament Fabrication, *AIM*, Munich, Germany, Jul., 2017.
140 G. Stano, L. Arleo and G. Percoco, *Micromachines*, 2020, **11**, 485.
141 S. Singh, G. Singh, C. Prakash and S. Ramakrishna, *J. Manuf. Process*, 2020, **55**, 288.
142 B. Derby, *Annu. Rev. Mater. Sci.*, 2010, **40**, 395.
143 G. Ponraj, S. K. Kirthika, C. M. Lim and H. L. Ren, *IEEE Sens. J.*, 2018, **18**, 9840.
144 L. Y. Zhou, Q. Gao, J. F. Zhan, C. Q. Xie, J. Z. Fu and Y. He, *ACS Appl. Mater. Interfaces*, 2018, **10**, 23208.
145 S. Schlatter, G. Grasso, S. Rosset and H. Shea, *Adv. Intell. Syst.*, 2020, **2**, 2000136.
146 R. MacCurdy, R. Katzschmann, Y. Kim and D. Rus, Printable Hydraulics: A Method for Fabricating Robots by 3D Co-Printing Solids and Liquids, Royal Inst Technol, Ctr Autonomous Syst, *IEEE ICRA*, Stockholm, Sweden, May, 2016.
147 J. A. Lewis and G. M. Gratson, *Mater. Today*, 2004, **7**, 32.
148 J. A. Lewis, *Adv. Funct. Mater.*, 2006, **16**, 2193.
149 A. G. Mark, S. Palagi, T. Qiu and P. Fischer, Auxetic Metamaterial Simplifies Soft Robot Design, Royal Inst Technol, Ctr Autonomous Syst, *IEEE ICRA*, Stockholm, Sweden, May, 2016.
150 S. S. Robinson, K. W. Obrien, H. Zhao, B. N. Peele, C. M. Larson, B. C. M. Murray, I. M. V. Meerbeek, S. N. Dunham and R. F. Shepherd, *Extreme Mech. Lett.*, 2015, **5**, 47.
151 M. A. Skylarscott, J. Mueller, C. W. Visser and J. A. Lewis, *Nature*, 2019, **575**, 330.
152 J. Choi, O. C. Kwon, W. Jo, H. J. Lee and M. W. Moon, *3D Print Addit. Manuf.*, 2015, **2**, 159.
153 S. Tibbits, *Archit. Des.*, 2014, **84**, 116.
154 S. Miao, W. Zhu, N. J. Castro, J. Leng and L. G. Zhang, *Tissue Eng., Part C*, 2016, **22**, 952.
155 N. Ashammakhi and O. Kaarela, *J. Craniofac. Surg.*, 2017, **28**, 1647.
156 C. Wang, K. Sim, J. Chen, H. Kim, Z. Rao, Y. Li, W. Chen, J. Song, R. Verduzco and C. Yu, *Adv. Mater.*, 2018, **30**, 1706695.
157 J. Liu, O. Erol, A. Pantula, W. Liu, Z. Jiang, K. Kobayashi, D. Chatterjee, N. Hibino, L. H. Romer and S. H. Kang, *ACS Appl. Mater. Interfaces*, 2019, **11**, 8492.
158 Q. Ge, A. H. Sakhaei, H. Lee, C. K. Dunn, N. X. Fang and M. L. Dunn, *Sci. Rep.*, 2016, **6**, 32355.
159 S. Janbaz, R. Hedayati and A. Zadpoor, *Mater. Horiz.*, 2016, **3**, 536.

160 B. Jin, H. Song, R. Jiang, J. Song, Q. Zhao and T. Xie, *Sci. Adv.*, 2018, **4**, eaao3865.
161 J. A.-C. Liu, J. H. Gillen, S. R. Mishra, B. A. Evans and J. B. Tracy, *Sci. Adv.*, 2019, **5**, eaaw2897.
162 S. Miao, H. Cui, T. Esworthy, B. Mahadik, S. J. Lee, X. Zhou, S. Y. Hann, J. P. Fisher and L. G. Zhang, *Adv. Sci.*, 2020, **7**, 2070034.
163 M. Sitti, H. Ceylan, W. Hu, J. Giltinan, M. Turan, S. Yim and E. Diller, *Proc. IEEE*, 2015, **103**, 205.
164 H. Cui, C. Liu, T. Esworthy, Y. Huang, Z. X. Yu, X. Zhou, H. San, S. J. Lee, S. Y. Hann and M. Boehm, *Sci. Adv.*, 2020, **6**, eabb5067.
165 W. Huang, Z. Ding, C. Wang, J. Wei, Y. Zhao and H. Purnawali, *Mater. Today*, 2010, **13**, 54.
166 L. Sun, W. M. Huang, Z. Ding, Y. Zhao, C. C. Wang, H. Purnawali and C. Tang, *Mater. Des.*, 2012, **33**, 577.
167 G. Stano and G. Percoco, *Extreme Mech. Lett.*, 2021, **42**, 101079.
168 D. Li, S. Wang, J. He, H. Zeng, K. Yao, Z. Gao, M. Wu, Y. Liu, L. Wang and Z. Xie, *Adv. Mater. Technol.*, 2021, **6**, 2001095.
169 C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador and P. Dario, *Adv. Robot.*, 2012, **26**, 709.
170 M. Wehner, R. L. Truby, D. J. Fitzgerald, B. Mosadegh, G. M. Whitesides, J. A. Lewis and R. J. Wood, *Nature*, 2016, **536**, 451.
171 N. El-Atab, R. B. Mishra, F. Al-Modaf, L. Joharji, A. A. Alsharif, H. Alamoudi, M. Diaz, N. Qaiser and M. M. Hussain, *Adv. Intell. Syst.*, 2020, **2**, 2000128.
172 A. D. Marchese, R. K. Katzschmann and D. Rus, *Soft Robot.*, 2015, **2**, 7.
173 X. Tang, K. Li, Y. Liu, D. Zhou and J. Zhao, *Smart Mater. Struct.*, 2019, **28**, 035019.
174 M. Calisti, M. Giorelli, G. Levy, B. Mazzolai, B. Hochner, C. Laschi and P. Dario, *Bioinspir. Biomim.*, 2011, **6**, 036002.
175 Y.-Y. Xiao, Z.-C. Jiang and Y. Zhao, *Adv. Intell. Syst.*, 2020, **2**, 2000148.
176 U. Gupta, L. Qin, Y. Wang, H. Godaba and J. Zhu, *Smart Mater. Struct.*, 2019, **28**, 103002.
177 J. G. Kim, J. E. Park, S. Won, J. Jeon and J. J. Wie, *Mater.*, 2019, **12**, 3065.
178 Y. F. Zhang, C. J. X. Ng, Z. Chen, W. Zhang, S. Panjwani, K. Kowsari, H. Y. Yang and Q. Ge, *Adv. Mater. Technol.*, 2019, **4**, 1900427.
179 S. G. Nurzaman, F. Iida, L. Margheri and C. Laschi, *Soft Robot.*, 2014, **1**, 154.
180 C. Majidi, *Soft Robot.*, 2014, **1**, 5.
181 L. Paez, G. Agarwal and J. Paik, *Soft Robot.*, 2016, **3**, 109.
182 R. F. Shepherd, A. A. Stokes, R. M. Nunes and G. M. Whitesides, *Adv. Mater.*, 2013, **25**, 6709.
183 J. Yi, X. Chen, C. Song and Z. Wang, *Soft Robot.*, 2018, **5**, 81.
184 R. Deimel and O. Brock, *Int. J. Robot. Res.*, 2016, **35**, 161.
185 W. Hu, R. Mutlu, W. Li and G. Alici, *Robotics*, 2018, **7**, 24.
186 P. Moseley, J. M. Florez, H. A. Sonar, G. Agarwal, W. Curtin and J. Paik, *Adv. Eng. Mater.*, 2016, **18**, 978.
187 F. Chen, S. Dirven, W. Xu and X. Li, *IEEE ASME Trans. Mechatronics*, 2013, **19**, 1300.
188 E. F. Gomez, S. V. Wanasinghe, A. E. Flynn, O. J. Dodo, J. L. Sparks, L. A. Baldwin, C. E. Tabor, M. F. Durstock, D. Konkolewicz and C. J. Thrasher, *ACS Appl. Mater. Interfaces*, 2021, **13**, 28870.
189 J. C. Yeo, H. K. Yap, W. Xi, Z. Wang, C. H. Yeow and C. T. Lim, *Adv. Mater. Technol.*, 2016, **1**, 1600018.
190 F.-Y. Xu, F.-Y. Jiang, Q.-S. Jiang and Y.-X. Lu, *IEEE Access*, 2020, **8**, 26356.
191 C. D. Onal, X. Chen, G. M. Whitesides and D. Rus, *Soft Mobile Robots with On-Board Chemical Pressure Generation*, Springer, Cham, Switzerland, 2017.
192 J. T. Overvelde, T. Kloek, J. J. D'haen and K. Bertoldi, *Proc. Natl. Acad. Sci. U. S. A.*, 2015, **112**, 10863.
193 H. Feng, Y. Sun, P. A. Todd and H. P. Lee, *Soft Robot.*, 2020, **7**, 233.
194 J. Bishop-Moser, G. Krishnan, C. Kim and S. Kota, Design of soft robotic actuators using fluid-filled fiber-reinforced elastomeric enclosures in parallel combinations, *IROS*, Vilamoura, Portugal, Oct., 2012.
195 K. C. Galloway, P. Polygerinos, C. J. Walsh and R. J. Wood, *Robot. Auton. Syst.*, 2014, **73**, 135.
196 A. D. Marchese, R. Tedrake and D. Rus, *Int. J. Robot. Res.*, 2016, **35**, 1000.
197 L. D. Pohlmann, *Insight*, 2014, **17**, 64.
198 M. Franke, A. Ehrenhofer, S. Lahiri, E. F. M. Henke, T. Wallmersperger and A. Richter, *Front. Robot. AI*, 2020, **7**, 510757.
199 F. Berlinger, M. Duduta, H. Gloria, D. Clarke, R. Nagpal and R. Wood, A Modular Dielectric Elastomer Actuator to Drive Miniature Autonomous Underwater Vehicles, *ICRA*, Brisbane, Australia, May, 2018.
200 E.-F. M. Henke, S. Schlatter and I. A. Anderson, *Soft Robot.*, 2017, **4**, 353.
201 C. T. Nguyen, H. Phung, H. Jung, U. Kim, H. R. Choi, J. Park, H. Moon, J. C. Koo and H. R. Choi, Printable monolithic hexapod robot driven by soft actuator, *IEEE ICRA*, Seattle, USA, May, 2015.
202 H. Godaba, J. Li, Y. Wang and J. Zhu, *IEEE Robot. Autom. Lett.*, 2016, **1**, 624.
203 E. Hajiesmaili and D. R. Clarke, *J. Phys. D*, 2021, **129**, 151102.
204 I. Must, E. Sinibaldi and B. Mazzolai, *Nat. Commun.*, 2019, **10**, 1.
205 J. Cao, L. Qin, J. Liu, Q. Ren, C. C. Foo, H. Wang, H. P. Lee and J. Zhu, *Extreme Mech. Lett.*, 2018, **21**, 9.
206 J. J. Keya, R. Suzuki, A. M. R. Kabir, D. Inoue, H. Asanuma, K. Sada, H. Hess, A. Kuzuya and A. Kakugo, *Nat. Commun.*, 2018, **9**, 1.
207 S. Hogreve, M. Prigge, K. O. Köbisch and K. Tracht, *Proc. CIRP*, 2020, **91**, 439.
208 M. C. Carrozza, G. Cappiello, E. Cavallaro, S. Micera, F. Vecchi and P. Dario, *Proc. World Automation Congress*, 2004, **15**, 111.
209 V. K. Venkiteswaran, D. K. Tan and S. Misra, *Extreme Mech. Lett.*, 2020, **41**, 101023.
210 D.-S. Choi, T.-H. Kim, S.-H. Lee, C. Pang, J. W. Bae and S.-Y. Kim, *ACS Appl. Mater. Interfaces*, 2020, **12**, 44147.

211 A. M. Nasab, A. Sabzehzar, M. Tatari, C. Majidi and W. Shan, *Soft Robot.*, 2017, **4**, 411.
212 Q. He, Z. Wang, Y. Wang, A. Minori, M. T. Tolley and S. Cai, *Sci. Adv.*, 2019, **5**, eaax5746.
213 J. Zhou, S. Chen and Z. Wang, *IEEE Robot. Autom. Lett.*, 2017, **2**, 2287.
214 C. J. Thrasher, J. J. Schwartz and A. J. Boydston, *ACS Appl. Mater. Inter.*, 2017, **9**, 39708.
215 D. K. Patel, A. H. Sakhaei, M. Layani, B. Zhang, Q. Ge and S. Magdassi, *Adv. Mater.*, 2017, **29**, 1606000.
216 P. Iacomi and G. Maurin, *ACS Appl. Mater. Interfaces*, 2021, **13**, 50602.
217 S. Schara, R. Blau, D. C. Church, J. K. Pokorski and D. J. Lipomi, *Adv. Funct. Mater.*, 2021, **31**, 2008375.
218 C. Cui, Q. Fu, L. Meng, S. Hao, R. Dai and J. Yang, *ACS Appl. Bio. Mater.*, 2020, **4**, 85.
219 T. Ube and T. Ikeda, *Angew. Chem., Int. Ed.*, 2014, **53**, 39.
220 J. Wang, J. Wang, Z. Chen, S. Fang, Y. Zhu, R. H. Baughman and L. Jiang, *Chem. Mater.*, 2017, **29**, 9793.
221 K. Mo, M. He, X. Cao and C. Chang, *J. Mater. Chem. C*, 2020, **8**, 2756.
222 J. C. Breger, C. Yoon, R. Xiao, H. R. Kwag, M. O. Wang, J. P. Fisher, T. D. Nguyen and D. H. Gracias, *ACS Appl. Mater. Interfaces*, 2015, **7**, 3398.
223 F. Ongaro, S. Scheggi, C. Yoon, F. V. den Brink, S. H. Oh, D. H. Gracias and S. Misra, *J. Microbio. Robot.*, 2017, **12**, 45.
224 K. Kobayashi, C. Yoon, S. H. Oh, J. V. Pagaduan and D. H. Gracias, *ACS Appl. Mater. Interfaces*, 2018, **11**, 151.
225 X. Fan, J. Y. Chung, Y. X. Lim, Z. Li and X. J. Loh, *ACS Appl. Mater. Interfaces*, 2016, **8**, 33351.
226 Q. Fu, H. Zhang, Z. Wang and M. Chiao, *J. Mater. Chem. B*, 2017, **5**, 4025.
227 J. Duan, X. Liang, K. Zhu, J. Guo and L. Zhang, *Soft Matter*, 2017, **13**, 345.
228 X. Li, X. Cai, Y. Gao and M. J. Serpe, *J. Mater. Chem. B*, 2017, **5**, 2804.
229 Y. Cheng, K. Ren, D. Yang and J. Wei, *Sens. Actuators, B*, 2018, **255**, 3117.
230 K. B. Justus, T. Hellebrekers, D. D. Lewis, A. Wood, C. Ingham, C. Majidi, P. R. LeDuc and C. Tan, *Sci. Robot.*, 2019, **4**, eaax0765.
231 C. Yang, Z. Liu, C. Chen, K. Shi, L. Zhang, X.-J. Ju, W. Wang, R. Xie and L.-Y. Chu, *ACS Appl. Mater. Interfaces*, 2017, **9**, 15758.
232 L. Chen, C. Liu, K. Liu, C. Meng, C. Hu, J. Wang and S. Fan, *ACS Nano*, 2011, **5**, 1588.
233 Z. S. Davidson, H. Shahsavan, A. Aghakhani, Y. B. Guo, L. Hines, Y. Xia, S. Yang and M. Sitti, *Sci. Adv.*, 2019, **5**, 11.
234 J. W. Zhou, H.-Y. Chan, T. K. To, K. W. Lai and W. J. Li, *IEEE ASME Trans. Mechatron*, 2004, **9**, 334.
235 E. Diller and M. Sitti, *Adv. Funct. Mater.*, 2014, **24**, 4397.
236 Z. Ji, C. Yan, B. Yu, X. Wang and F. Zhou, *Adv. Mater. Int.*, 2017, **4**, 1700629.
237 J. Zhang, O. Onaizah, K. Middleton, L. You and E. Diller, *IEEE Robot. Autom. Lett.*, 2017, **2**, 835.
238 H. Yuk, S. Lin, C. Ma, M. Takaffoli, N. X. Fang and X. Zhao, *Nat. Commun.*, 2017, **8**, 1.
239 C. Li, G. C. Lau, H. Yuan, A. Aggarwal, V. L. Dominguez, S. Liu, H. Sai, L. C. Palmer, N. A. Sather and T. J. Pearson, *Sci. Robot.*, 2020, **5**, eabb9822.
240 X. Zhang, Z. B. Yu, C. Wang, D. Zarrouk, J. W. T. Seo, J. C. Cheng, A. D. Buchan, K. Takei, Y. Zhao, J. W. Ager, J. J. Zhang, M. Hettick, M. C. Hersam, A. P. Pisano, R. S. Fearing and A. Javey, *Nat. Commun.*, 2014, **5**, 2983.
241 B. Zuo, M. Wang, B. P. Lin and H. Yang, *Nat. Commun.*, 2019, **10**, 4539.
242 Z. Ali, Z. K. Abbas, N.-N. Bijan, A. Scott, K. Sui Yang, N. Michael, G. Ian and K. Akif, *KnE Eng.*, 2017, **2**, 15.
243 D. Hua, X. Zhang, Z. Ji, C. Yan, B. Yu, Y. Li, X. Wang and F. Zhou, *J. Mater. Chem. C*, 2018, **6**, 2123.
244 Y. Y. Yang, Y. T. Liu and Y. J. Shen, *Adv. Funct. Mater.*, 2020, **30**, 14.
245 P. Zhou, L. Chen, L. Yao, M. Weng and W. Zhang, *Nanoscale*, 2018, **10**, 8422.
246 J. M. Jani, M. Leary, A. Subic and M. A. Gibson, *Mater. Des.*, 2014, **56**, 1078.
247 M. C. Biswas, S. Chakraborty, A. Bhattacharjee and Z. Mohammed, *Adv. Funct. Mater.*, 2021, **31**, 2100257.
248 Y. Xia, Y. He, F. Zhang, Y. Liu and J. Leng, *Adv. Mater.*, 2021, **33**, 2000713.
249 M. Behl, K. Kratz, J. Zotzmann, U. Nöchel and A. Lendlein, *Adv. Mater.*, 2013, **25**, 4466.
250 Q. Ze, X. Kuang, S. Wu, J. Wong, S. M. Montgomery, R. Zhang, J. M. Kovitz, F. Yang, H. J. Qi and R. Zhao, *Adv. Mater.*, 2020, **32**, 1906657.
251 Y. Chen, X. Zhao, Y. Li, Z.-Y. Jin, Y. Yang, M.-B. Yang and B. Yin, *J. Mater. Chem. C*, 2021, **9**, 5515.
252 M. Liu, S. Zhu, Y. Huang, Z. Lin, W. Liu, L. Yang and D. Ge, *Composites, Part B*, 2021, **214**, 108748.
253 X. L. Pang, L. Qin, B. Xin, Q. Liu and Y. L. Yu, *Adv. Funct. Mater.*, 2020, **30**, 32.
254 J.-H. Lee, Y. S. Chung and H. Rodrigue, *Sci. Rep.*, 2019, **9**, 1.
255 H. Rodrigue, W. Wang, D.-R. Kim and S.-H. Ahn, *Compos. Struct.*, 2017, **176**, 398.
256 F. Simone, G. Rizzello and S. Seelecke, *Smart Mater. Struct.*, 2017, **26**, 095007.
257 W. Wang and S.-H. Ahn, *Soft Robot.*, 2017, **4**, 379.
258 Y. She, J. Chen, H. Shi and H.-J. Su, *Soft Robot.*, 2016, **3**, 71.
259 K. Nakajima, H. Hauser, T. Li and R. Pfeifer, *Soft Robot.*, 2018, **5**, 339.
260 B. Shih, D. Shah, J. Li, T. G. Thuruthel, Y.-L. Park, F. Iida, Z. Bao, R. Kramer-Bottiglio and M. T. Tolley, *Sci. Robot.*, 2020, **5**, eaaz9239.
261 T. G. Thuruthel, B. Shih, C. Laschi and M. T. Tolley, *Sci. Robot.*, 2019, **4**, eaav1488.
262 P. Preechayasomboon and E. Rombokas, *Actuators*, 2021, **10**, 30.
263 R. L. Truby, C. Della Santina and D. Rus, *IEEE Robot. Autom. Lett.*, 2020, **5**, 3299.
264 L. Weerakoon, Z. Ye, R. S. Bama, E. Smela, M. Yu and N. Chopra, Adaptive Tracking Control of Soft Robots Using

Integrated Sensing Skins and Recurrent Neural Networks, *ICRA*, Xi'an, China, May, 2021.
265 T. Jin, Z. Sun, L. Li, Q. Zhang, M. Zhu, Z. Zhang, G. Yuan, T. Chen, Y. Tian and X. Hou, *Nat. Commun.*, 2020, **11**, 1.
266 K. Chin, T. Hellebrekers and C. Majidi, *Adv. Intell. Syst.*, 2020, **2**, 1900171.
267 M. Sitti, *Nat. Rev. Mater.*, 2018, **3**, 74.
268 A. De Greef, P. Lambert and A. Delchambre, *Precis. Eng.*, 2009, **33**, 311.
269 D. B. Comber, J. E. Slightam, V. R. Gervasi, J. S. Neimat and E. J. Barth, *IEEE Trans. Robot.*, 2016, **32**, 138.
270 K. Suzumori, A. Koga, F. Kondo and R. Haneda, *Robotica*, 1996, **14**, 493.
271 L. Ricotti, B. Trimmer, W. Feinberg Adam, R. Raman, K. Parker Kevin, R. Bashir, M. Sitti, S. Martel, P. Dario and A. Menciassi, *Sci. Robot.*, 2017, **2**, eaaq0495.
272 S. Fusco, M. S. Sakar, S. Kennedy, C. Peters, R. Bottani, F. Starsich, A. Mao, G. A. Sotiriou, S. Pané and S. E. Pratsinis, *Adv. Mater.*, 2014, **26**, 952.
273 J. C. Breger, C. Yoon, R. Xiao, H. R. Kwag, M. O. Wang, J. P. Fisher, T. D. Nguyen and D. H. Gracias, *ACS Appl. Mater. Interfaces*, 2015, **7**, 3398.
274 K. E. Gordon, G. S. Sawicki and D. P. Ferris, *J. Biomech.*, 2006, **39**, 1832.
275 B. G. Do Nascimento, C. B. S. Vimieiro, D. A. P. Nagem and M. Pinotti, *Artif. Organs*, 2008, **32**, 317.
276 S. Wang, Z. Sun, Y. Zhao and L. Zuo, *Sens. Actuators, A*, 2021, **331**, 113006.
277 H. Banerjee and H. Ren, *Soft Robot.*, 2017, **4**, 191.
278 B. Xu, X. Han, Y. Hu, Y. Luo, C. H. Chen, Z. Chen and P. Shi, *Small*, 2019, **15**, 1900006.
279 Z. Ren, R. Zhang, R. H. Soon, Z. Liu, W. Hu, P. R. Onck and M. Sitti, *Sci. Adv.*, 2021, **7**, eabh2022.
280 H. Abidi, G. Gerboni, M. Brancadoro, J. Fras, A. Diodato, M. Cianchetti, H. Wurdemann, K. Althoefer and A. Menciassi, *Int. J. Med. Robotics Comput. Assist. Surg.*, 2018, **14**, e1875.
281 E. B. Joyee and Y. Pan, *J. Manuf. Process*, 2020, **56**, 1178.
282 O. P. Ogunmolu, X. Gu, S. Jiang and N. R. Gans, *Med. Phys.*, 2016, **42**, 3266.
283 S. S. Yun, S. Yi, R. Brand, J. V. Zitzewitz and S. Micera, Soft robot for gait rehabilitation of spinalized rodents, *IROS*, Tokyo, Japan, Nov., 2014.
284 L. Lindenroth, S. Bano, A. Stilli, J. G. Manjaly and D. Stoyanov, *IEEE Robot. Autom. Lett.*, 2021, **6**, 871.
285 M. Cianchetti, C. Laschi, A. Menciassi and P. Dario, *Nat. Rev. Mater.*, 2018, **3**, 143.
286 P. Polygerinos, N. Correll, S. A. Morin, B. Mosadegh, C. D. Onal, K. Petersen, M. Cianchetti, M. T. Tolley and R. F. Shepherd, *Adv. Eng. Mater.*, 2017, **19**, 1700016.
287 M. Runciman, A. Darzi and G. P. Mylonas, *Soft Robot.*, 2019, **6**, 423.
288 S. Terryn, J. Brancart, D. Lefeber, G. Van Assche and B. Vanderborght, *Sci. Robot.*, 2017, **2**, eaan4268.
289 S. Y. Hann, H. Cui, M. Nowicki and L. G. Zhang, *Addit. Manuf.*, 2020, **36**, 101567.
290 H. Wang, R. Zhang, W. Chen, X. Wang and R. Pfeifer, *Surg. Endosc.*, 2017, **31**, 3152.
291 T. Deng, H. Wang, W. Chen, X. Wang and R. Pfeifer, Development of a new cable-driven soft robot for cardiac ablation, *ROBIO*, Shenzhen, China, Dec, 2013.
292 J. Tang, C. Yao, Z. Gu, S. Jung, D. Luo and D. Yang, *Angew. Chem., Int. Ed.*, 2020, **132**, 2511.
293 W. Hu, G. Z. Lum, M. Mastrangeli and M. Sitti, *Nature*, 2018, **554**, 81.
294 T. Roche Ellen, A. Horvath Markus, I. Wamala, A. Alazmani, S.-E. Song, W. Whyte, Z. Machaidze, J. Payne Christopher, C. Weaver James, G. Fishbein, J. Kuebler, V. Vasilyev Nikolay, J. Mooney David, A. Pigula Frank and J. Walsh Conor, *Sci. Trans. Med.*, 2017, **9**, eaaf3925.
295 H. Wang, M. Totaro and L. Beccai, *Adv. Sci.*, 2018, **5**, 1800541.
296 U. Culha, U. Wani, S. G. Nurzaman, F. Clemens and F. Iida, *Sensors*, 2014, **14**, 12748.
297 C. Mattmann, F. Clemens and G. Tröster, *Sensors*, 2008, **8**, 3719.
298 M. Amjadi, K. U. Kyung, I. Park and M. Sitti, *Adv. Funct. Mater.*, 2016, **26**, 1678.
299 Y.-L. Park, B.-R. Chen and R. J. Wood, *IEEE Sens. J.*, 2012, **12**, 2711.
300 J.-B. Chossat, Y.-L. Park, R. J. Wood and V. Duchaine, *IEEE Sens. J.*, 2013, **13**, 3405.
301 X. Xiao, L. Yuan, J. Zhong, T. Ding, Y. Liu, Z. Cai, Y. Rong, H. Han, J. Zhou and Z. L. Wang, *Adv. Mater.*, 2011, **23**, 5440.
302 Y. R. Jeong, H. Park, S. W. Jin, S. Y. Hong, S. S. Lee and J. S. Ha, *Adv. Funct. Mater.*, 2015, **25**, 4228.
303 M. Amjadi, A. Pichitpajongkit, S. Lee, S. Ryu and I. Park, *ACS Nano*, 2014, **8**, 5154.
304 C. Mattmann, O. Amft, H. Harms, G. Troster and F. Clemens, *Sensors*, 2008, **8**, 3719.
305 J. Hughes and F. Iida, *Soft Robot.*, 2018, **5**, 512.
306 Z. Yang, S. Ge, F. Wan, Y. Liu and C. Song, Scalable Tactile Sensing for an Omni-adaptive Soft Robot Finger, *RoboSoft*, New Haven, The United States, Jul., 2020.
307 T. Gao, D. Li, G. Jin, H. Liang and R. Yang, *Nano-Micro Lett.*, 2018, **13**, 1460.
308 X. Tang, K. Li, Y. Liu and J. Zhao, *IEEE Sens. J.*, 2018, **18**, 6123.
309 Q. He and Q. Zhang, *Optoelectron. Lett.*, 2021, **17**, 400.
310 A. Kakogawa and S. Ma, *Adv. Robot.*, 2012, **26**, 253.
311 T. Oya and T. OkadaA, *Adv. Robot.*, 2005, **19**, 635.
312 K. Isaki, A. Niitsuma, M. Konyo, F. Takemura and S. Tadokoro, Development of an Active Flexible Cable by Ciliary Vibration Drive for Scope Camera, *IROS*, Beijing, China, Oct, 2006.
313 S. M. Liu and W. J. Shang, *Machinery*, 2009, **36**, 76.
314 Y. H. Chen, Q. Y. Liu and T. Ren, *Robotica*, 2015, **33**, 920.
315 J. W. Qiao, J. Z. Shang, X. Chen, Z. R. Luo and X. P. Zhang, *J. Cent. South Univ. Technol.*, 2010, **17**, 1043.
316 Z. Zhang, X. Wang, S. Wang, D. Meng and B. Liang, *IEEE Access*, 2019, **7**, 134301.
317 R. Bogue, *Ind Robot.*, 2013, **37**, 421.
318 X. Zhang, T. Pan, H. L. Heung, P. W. Y. Chiu and Z. Li, A biomimetic soft robot for inspecting pipeline with

significant diameter variation, *IROS*, Madrid, Spain, Oct., 2018.
319 A. A. Calderón, J. C. Ugalde, J. C. Zagal and N. O. Pérez-Arancibia, Design, fabrication and control of a multi-material-multi-actuator soft robot inspired by burrowing worms, *ROBIO*, Macau, China, Dec., 2017.
320 B. Zhang, Y. Fan, P. Yang, T. Cao and H. Liao, *Soft Robot.*, 2019, **6**, 399.
321 Y. Y. Xiao, Z. C. Jiang, X. Tong and Y. Zhao, *Adv. Mater.*, 2019, **31**, 1903452.
322 Y. Tang, Q. Zhang, G. Lin and J. Yin, *Soft Robot.*, 2018, **5**, 592.

