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Recent Advances in Biomimetic Soft Robotics: Fabrication Approaches, Driven Strategies and Applications

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Abstract

Soft robots, compared to traditional rigid-bodied robots, are constructed with physically flexible/elastic bodies and electronics to mimic nature and enable novel applications in industry, healthcare, aviation, military, etc. Recently, building on soft matters of great flexible and compliance allows smooth and sophisticated 'multi-degree-of -freedom' 3D actuation to seamlessly interact with humans, other organisms and non-idealized environments in highly complex and controllable manners. Here, we summarize the fabrication approaches, driving strategies, novel applications, and future trends of soft robots. Firstly, the different fabrication approaches to prepare soft robots are introduced, and their advantages and disadvantages are compared and systematically discussed. Then, the actuator-based and material-based driving strategies of soft robotics and their characteristics are presented. The representative applications of soft robotics for artificial intelligence, medical, sensors, and engineering are summarized. Some remaining challenges and future perspectives in soft robotics are also provided. This work highlights the recent advances of soft robotics, in terms of functional materials selection, structure design, control strategies and biomimicry, which provides useful insights into the development of the new generation of functional soft robotics.

Key Words: Soft Robots; Fabrication Approaches; Driving Strategies; Artificial Intelligence; Medical; Sensors; Engineering.

1. Introduction

As semi-automatic or fully automatic intelligence machine, robots have some basic characteristics, for instance, cognitive capabilities, decision-making, 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 grew rapidly as an interdisciplinary field, and 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, as compared to 'systems or mechanisms' built by Nature-living organisms. However, the performance of the mechanical structure, intelligence and stability of control software, and reliable design of circuitry is needed to be considered. Due to this simplification and flexibility and 3D actuation capability of rigid-bodied robotics are substantially limited.[7-9] More specifically, rigid robots are usually expensive to prepare and can only work in a predetermined environment. Routinely, due to the use of rigid metallic, plastic and ceramic materials, rigid links connected, and relatively large volumes, their degrees of freedom (DoF) are significantly limited, so they fall short 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 issue and many become one of the trends of future research.[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 a system capable of autonomous behavior, mainly composed of materials with a modulus in the range of soft biological materials.[16] Compared with conventional hard robots, soft robot's complete difficult 3D actuation with low mechanical impedance and relatively high compliance in a safe state. In addition, designing the performance of the soft robots can make them pick up objects hundreds of times their weight and have more excellent characteristics.[17-20] For the design and preparation of soft robots, available material and manufacturing structures are two important key points. In addition, bioinspiration plays an important role in the preparation of soft robots. Bio-inspiration systems usually take into account the morphology, characteristics, and motion states of organisms. Researchers have taken inspiration from many organisms to prepare soft robots with functional characteristics successfully, such as chameleon,[21] worms, [22-24] fish,[25-27] snake,[28] octopus,[29,30] and frogs. [31] In the beginning, flexible elastomer materials were used to prepare soft robots, such as polymers, silicone rubber. [18,32] With the advancement of research, to make the soft robots more intelligent, some smart materials such as stimuli-responsive materials (SRM) that can respond to stimuli from the environment (e.g. thermal, light, electricity, mechanical, chemical. [33-35]) 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 that they can be restored to the initial state by external stimuli after deformation.[36] The fundamental reason for deformation and recovery is that SMAs transit the material's crystalline structure and releases stored elastic energy under temperature changes.[29,37] SMPs have similar characteristics, and they exhibit lower density, stiffness, and energy release during their transition.[38] About manufacturing structures, to create compliant mechanisms, some soft robots are still rigid link system[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 origami and kirigami techniques to design special structures that can be flexible motioned around a given axis and have a high off-axis stiffness when exposed to mechanical over-constraints is a wisdom approach as well.[28,46-48] With the development of technology, soft robots innovatively are designed and manufactured rather than artificially assembled by elementary blocks. However, the preparation of soft robots still faces challenges and opportunities, and real technological breakthrough is still imminent.[49-52]

Research and development of soft robots first need to purposefully consider the functions and the application scenarios, and then realize it by designing the structure and selecting appropriate materials. To improve preparation efficiency, it is necessary to combine some appropriate preparation methods. Some reviews about soft robots have been published in recent years, including design and fabrication process,[3,16,53,54] materials selected,[55-59] manufacturing methods,[60-63] actuation technologies,[64] application occasion,[65] etc. 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 representative studies and recent advances in soft robotics, including the popular preparation approaches of soft robots (section 2), driven strategies (actuator-based and materials-based) (section 3), and the emerging applications (i.e., artificial intelligence, medical, sensors, and others) (section 4). The challenges and perspectives of soft robotics are also 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 classified the fabrication approaches of soft robots into three types: i) top-down approaches (i.e., template-assisted casting method, laser, or soft lithography to define polymer objects), ii) bottom-up approaches (i.e., adding reinforcement and additive manufacturing solutions), iii) a combination of top-down and bottom-up approaches: several subparts of the soft robots are prepared in various ways, and the overall fabrication requires a combination of above approaches. In addition, the fabrication and synthesis of some important components of the soft robots will become the content of this chapter as well.

2.1 Molding

Molding is a relatively low-cost and convenient fabrication method that creating something by casting it in a mold, and it is relatively suitable for the preparation of large size (such as centimeter, decimeter, meter level) and the structures with chambers of soft robot. Molding has a wide range of applications in the early biomimetic soft robots (e.g., fish,[25] earthworm,[66] cephalopod molluscs[67]). However, the soft robots fabricated by the molding method may have air bubbles mixed into materials during the preparation process, which may weaken the final structures of the soft robots, further affecting the quality. Vacuum degassing the mixture, spinning the mold, shaking the molding or using centrifugal force can effectively eliminate the bubbles generated during the fabrication and synthesis of the soft robots.[68-70] Manufacturing complex internal structures, volumes and undercuts is a difficult problem to solve as well. The emerging lost-wax casting can achieve arbitrarily shape internal channels, thus solving the above problems to a certain extent.[71-73]

The method of the molding continues to be subdivided into multiple ways, such as rotational molding, multi-step molding, vacuum casting, infusion molding, injection molding etc. Different molding modes correspond to various types of materials, and have corresponding functions as well, such as infusion molding which is usually used to fabricate fiber-reinforced composites, can be adapted to soft composites with fibrous matrix as well.[69] In terms of injection molding, due to the high cost of the machine, large volumes of liquid silicones required, and the difficulty to change materials quickly between injections, this technology has not been popularized in 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, or cure times are presented.[60,74-76] There are some representative examples about other different kinds of molding methods in the following.

Rotational molding is a method, whose most obvious advantages is it can simplify the soft machine fabrication process. Shepherd and co-workers used rotational casting method to fabricate monolithic soft machines by 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 over similar research reported.[77] In addition, they prepared a wearable assistive device that users can apply force at their fingertips by rotational molding fabrication approach, and the rotational casting machine with multiple molds is shown in **Figure 1a**. The prepared rotational cast part consists of a series of separate units connected by a common flat layer. A steel wire is passed through each chamber and encapsulated with the same elastomer to ensure that compressed air can be applied to each unit. The prepared cuboid actuator can achieve a good bending effect at 40 kPa (in **Figure 1b**). Based on above cuboid actuator, they prepared a system that uses electromyography (EMG) sensors and microcontrollers to open and close solenoid valves based on compressed air to power finger actuators.[78] In addition, the rotational molding, as a fast and convenient way to prepare soft robots plays an important role in verifying the simulation results. Kriegman and co-workers prepared voxels by a single-axis rotational molding machine which were poured silicone into the acrylic mold (in **Figure 1c**). And they used the prepared soft robots to simulate, manufacturing, and measure the simulation-reality gap of minimally complex yet soft, locomoting machines. They proved that this fabricated method is more scalable than other robots that move from simulation to reality.[79]

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

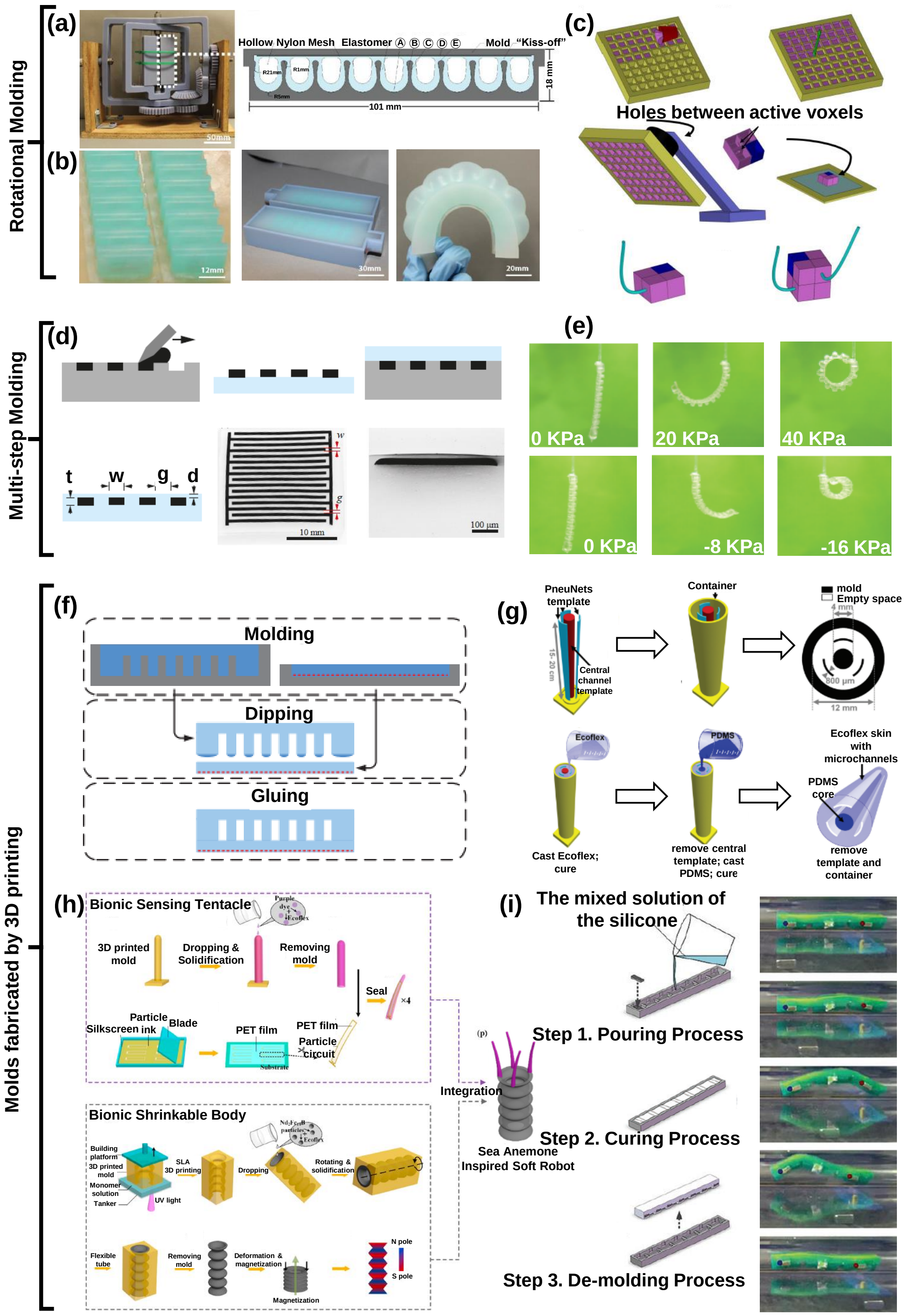


Figure 1. (a) Rotational cast machine and the interior structure of a cuboid soft actuator mold and elastomer coating. (b) The cuboid actuator casting process and finished inflation actuator.[78] Copyright 2015, Elsevier. (c) The process of manufacturing modular soft robots.[79] Copyright 2020, IEEE. (d) Fabrication process schematic of stretchable electro adhesion for soft robots.[80] Copyright 2014, IEEE. (e) Experimental

results of curling actuators which are fabricated by molding with positive and negative pressure.[32] Copyright 2008, IEEE. (f) Fabrication procedure schematic of fluidic elastomer actuator modules.[81] Copyright 2012, IEEE. (g) Fabrication process of the 3D tentacles. First, prepare the mold by 3D printing, then use two different materials to pour into the mold, and finally get the 3D tentacle by demolding.[82] Copyright 2012, Wiley-VCH. (h) The fabrication process of soft robots inspired by sea anemone.[83] Copyright 2021, Elsevier. (i) The fabrication process of soft robots inspired by worm.[84] Copyright 2020, Mary Ann Liebert, Inc.

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

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

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

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

2.2 Etching, Laser or Soft Lithography

Micro robotics exhibit perfect performance but due to their small size, they are usually more difficult in the process of preparation. Etching, laser, and soft lithography methods are emerging to better fabricate and synthesis relatively small-scale soft robots, such as micron scale. Often than not, the preparation methods are suitable for improving large macroscope soft robots as well (such as millimeter, centimeter level), and these methods can be understood as modifying the structures of the soft objects with external assistance to achieve hyperfine structures with simple steps. However, the cost of equipment is relatively high, and the operation of the devices sometimes need certain requirements for the environment.[86-88]

Etching is a technology that removes materials by using 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 the conductive fabric base material, resulting in different conductive surfaces in the same textile. They connected distinct conductive surfaces via a flexible wire bus embedded in silicone and terminate in a flexible PCB. The collection of soft capacitive sensing strips and soft pneumatic actuators with embedded sensors manufactured with PCB etching technology can be seen in **Figure 2a**. The prepared soft robotic can use capacitive touch sensing to interact with conductive objects in the environment. When the actuator is inflated from 5 psi to 6 psi, the actuator successfully pushes the metal can to the left, and when the actuator is deflated to 5 psi, the actuator no longer touches the can (in **Figure 2b**). The dependence on conductive objects may be a possible limitation of capacitive pre-touch sensing approach. However, this could be leveraged as an asset in some applications. [91]

Regarding the fabrication and synthesis of soft robots, laser method can be divided into different forms such as laser etched,[92] laser imaging,[93] laser ablation,[94] laser cut.[18] Different materials and required structures correspond to different laser technology preparation methods. Jiang et al. used laser-etched method to prepare individual patterns in the stretchable hydrophobic smart film which is fabricated by graphene-polymer/ SiO_2 composite. The film possesses variable surface wettability and excellent stability to high tensile strain, and has broad application prospects in soft robots (in **Figure 2c**).[92] For the fabrication of the relatively 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 has strong pressure resistance and can adapt to various environments (indoors and outdoors).[18] Yang et al. used laser cutting technology to fabricate a soft gripper which is inspired by thin and elastic kirigami shell. By combining experiments, finite element simulations, and theoretical modeling, the design of gripper can be both scalable and material independent.[48] There is an interesting work related to sample preparation by laser, Deng et al. prepared a special laser rewritable magnetic composite film that can be digitally and repeatedly reprogrammed by direct laser writing method. The composite film is composed of elastomer and magnetic particles encapsulated by a phase change polymer. When laser irradiation generated heat, the orientation of the magnetic particles can be rearranged according to changes in the programming magnetic field. By encoding an anisotropic magnetic field in the composite film, the film can generate multimodal 3D shaping by the same magnetic field (in **Figure 2d**). This work has an important guiding significance for the preparation of reconfigurable soft robots.[95]

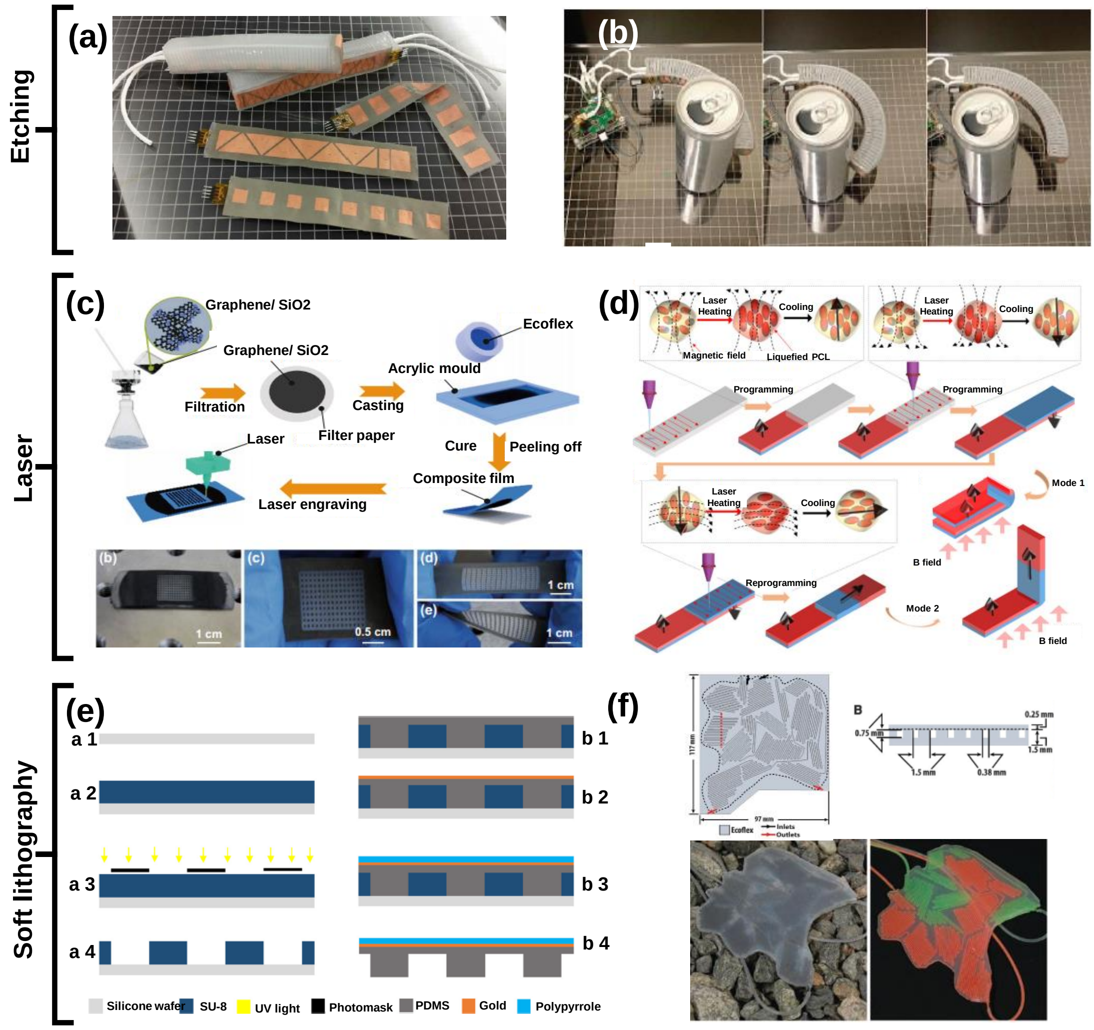


Figure 2. (a) Pictures of embedded sensor manufactured by PCB etching technology. (b) A sequence of images accompanying the objects' interactive experiments.[91] Copyright 2017, IEEE. (c) Fabrication process and pictures of the stretchable hydrophobic smart film.[92] Copyright 2019, Springer Nature. (d) The fabrication process of the soft gripper and the experiment and the FEA simulation schematics.[95] Copyright 2020, Springer Nature. (e) Schematic of the actuator's process flow. Spin coat photoresist SU-8 on the clean silicon substance, through UV exposure to dissolve uncured photoresist. Pour PDMS and evaporate a thin layer of gold. Then, electropolymerize a thick layer of polypyrrole. Finally, careful release the PDMS layer

from silicon substance.[98] Copyright 2019, Springer Nature. (f) Design and operation of the color layer of the soft robot.[101] Copyright 2012, American Association for the Advancement of Science.

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 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 phase-shift mask, optical proximity effect correction and double-layer glue.[96] It has gradually become one of the most common approaches to prepare soft elastomer robots due to the characteristics of being convenient, efficient, and low cost to manufacture micro and nano structures.[97] The simplicity of soft lithography allows rapid iterative design. With reference to this feature, Shepherd et al. used soft lithography technology to prepare pneumatic soft robot with complex motions.[3] Tyagi et al. employed soft lithography to pattern and fabricate polydimethylsiloxane layers with geometrical pattern, and they use this technology as a construction element to prepare the micro actuators, the process flow of the actuator is shown in **Figure 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 are 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 a cheap but powerful synthetic morphogenetic system 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 is composed of three layers which is able to provide a wide range of non-linear motions.[100] There is an interesting research, Morin et al. used soft lithography adapted from microfluidics to prepare a color-changing soft machine composed of soft polymers and flexible reinforcing sheets (in **Figure 2f**). The color, contrast, pattern, appearance shape, luminescence and surface temperature of soft machines used for camouflage and display can be changed through the microfluidic network, which is of great significance for the study of anti-counterfeiting and other fields.[101] It can be seen from above that soft lithography technology plays an important role in the design and manufacture of pneumatically actuated soft system in composite materials composed of silicone polymers and elastomers.

A report study combined lithography with other technologies (such as mold-assisted lithography) to fabricate and synthesis soft robots as well. Mosadegh et al. used 3D printing to prepare basic molds, and then used these molds for soft lithography to fabricate soft robots fPNs with a pneumatic network that the digital syringe pump provides a constant flow rate for both inflation and deflation of the fPNs. The fPNs actuated quickly, and compared with previous relative soft robots, the oversize and power-consumption of fPNs are reduced, while the durability performance is 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 preparation will be 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 efficiently assembling objects layer-by-layer from smaller pieces of materials. 3D printing has requirements for the materials, such as the size and the uniform of the particles of the materials, the good fluidity, and certain curing properties.[103-106] In recent years, these 3D printing technologies have been widely used in the preparation of soft robots. 3D printed products have the characteristics of high quality, low cost, environmentally and ecologically favorable, 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, the results showed that the soft robot prepared by 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 conventional photolithography technique costs are high and require clean room facilities. Stereolithography (SLA) technique appears to reduce the complexity of the soft robotics' fabrication. It's worth noting that there are certain requirements (such as elasticity, viscosity, composition) for the selection of polymer materials when using stereo lithography.[109,110] Chan et al. incorporated acrylic-PEG-collagen into a photopoly-merizable PEGDA hydrogel (PEGDA-PC), and used the stereolithography technique (a layer-by-layer UV polymerizable rapid prototyping system) to fabricate a multiple-material hydrogel actuators and cantilevers which the elasticity up to 103 KPa (in **Figure 3a**). The cantilever prepared by this work is as compliant as the cantilever of native myocardium, and will be an early prototype for designing optimal cell-based biohybrid actuators.[111] Peele et al. used stereolithography technique to prepare artificial muscle with soft structures that could interact and mimic the biological systems.[112] Shiblee et al. printed shape memory hydrogel (SMG) by stereolithographic technology to fabricate two different samples which the concentrations of stearyl acrylate (SA) and dimethyl acrylamide (DMAAm) monomer are various. This is a novel technology for preparing SMG actuators.[113] In addition, some accessories prepared using SLA are expected to use in the field of soft robotics.[114-116]

Selective laser sintering (SLS) is one of the 3D printing technologies that uses a laser as 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 productions 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 multi-arm inspired by snake, and the structures made by SLS can bear a weight around 800 g, it 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 nylon and graphite mixed powder, and the preparation process is shown in **Figure 3b**. This film has good flexibility and allows 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 with no 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, and it 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 some polymer materials have better curing and modelling properties, SDM also played a certain role in the process of preparing the grasper.[128,129] Gafford et al. used SDM to prepare a multijointed grasper frame. The prepared gripper does not use friction or pinching but uses geometric trapping to manipulate tissues. The prepared soft robot eliminates 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 (in **Figure 3c)**.[128]

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

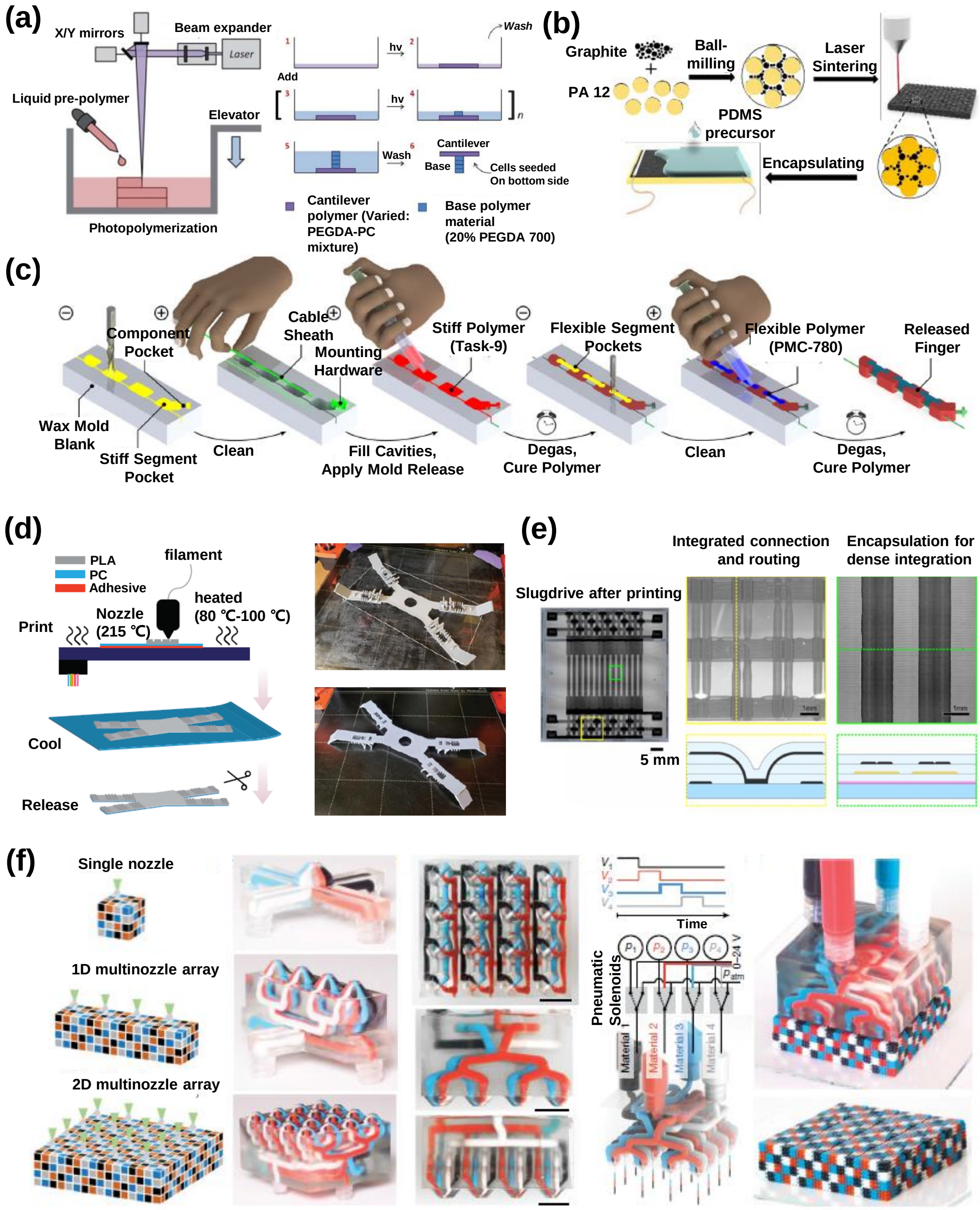


Figure 3. (a) The schematic diagram of multi-material cantilever fabricated by SLA.[111] Copyright 2012, Royal Society of Chemistry. (b) Schematic of the fabrication process of the composite-material sensor through SLS technology.[124] Copyright 2019, Royal Society of Chemistry. (c) The whole process of preparing finger model using SDM method.[128] Copyright 2015, ASME. (d) Using FDM method to prepare the process of 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) The schematic diagram of MM3D process.[151] Copyright 2019, Springer Nature.

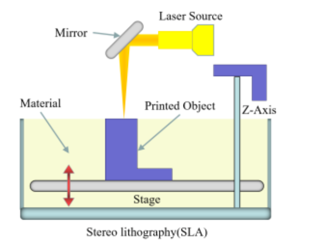
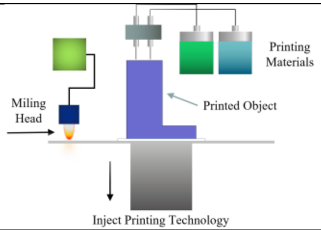
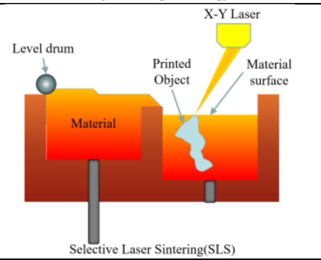
Fused deposition modelling (FDM), is one of the most popular 3D printing technologies, due to its low cost and straightforward has been widely used in industrial applications and become the most accessible 3D printing alternative for the general public.[130] There is research on the preparation of sensors with FDM technology in recent studies, which is of great significance for the future application in soft robots.[131,132] Some soft robots fabricated with FDM technology have realized functional applications, and have successfully achieved grasping[133] and actuating.[134] In addition, Teoh et al. fabricated an undulating soft robot inspired by 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 the hybrid soft and rigid robots. This work has significantly improved the fatigue resistance of printed components and achieved a new class of Robot form inspired by insects (in **Figure 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]

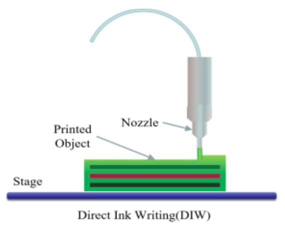
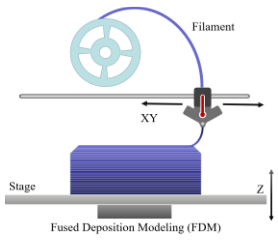
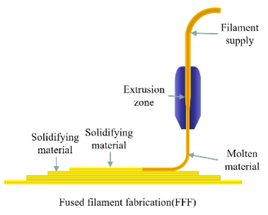
Inkjet printing, as one of 3D printing technologies, is a digital printing process to print a digital-based image directly by getting small droplets of ink in rapid succession.[142] Due to inkjet printing can produce mass high accuracy productions with low cost, it is used to fabricate sensors, such as soft tactile sensor,[143] wearable sensor.[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. Cross-sections and close-ups of electrical vias and high-voltage zipping electrodes of actuator illustrate the superior performance of inkjet printing technology (in **Figure 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 call it a printable hydraulic system, which can be completed by different functions of a hydraulically driven soft robot structure. And successfully prepared a hydraulically driven hexapod soft robot.[146]

Direct ink writing (DIW) is a preparation method for the translation stage controlled by the computer creating controlled architecture and composition of materials through ink deposition nozzle.[147] DIW can achieve pattern functional materials in complex 3D architectures from a broad array of materials rapidly. However, when it comes to 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 uses mechanical metamaterials to achieve the internal synchronization of the two passive clutches contacting its traveling surface. Doing so allows 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 sensory motor onto soft, fluidic elastomer actuators (FEAs). Sensors are fabricated to allow tangible perception and kinesthetic responses in pneumatically stimulated tactile devices. According to the report, the capacitive skin allows to detect a pressure of ~2 N generated by pressing its top surface with a finger, and the internal pressure is around 10 kPa.[150]

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

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, print materials with multiple attributes	Support required, unused materials are toxic and flammable, warping, sticky unused materials	PEGDA-collagen hydrogel	[111]
				Resin vat constructed from borosilicate glass with a thin layer of Sylgard 184 (PDMS)	[112]
				Poly(mercaptopropyl) methylsiloxane-co-dimethylsiloxane and PDMS	[114]
				Spot E elastic resin, EMG 1200 dry magnetic nanoparticles	[116]
Selective laser sintering (SLS)		No support required, parts with high mechanical properties	Printing equipment is relatively large and expensive	Elastic silicon materials	[122]
				A polymer powder named PA 2200 with a particle	[123]
				Graphite, PA12	[124]
Shape deposition modelling (SDM)		Fabricate complex geometries with heterogeneous materials, rapid prototyping	High control is required	Task-9TM Polyurethane (stiff segment), PMC-780TM urethane rubber(flexible segment)	[128]
				Two parts of industrial polyurethanes, IE35A, IE90A, IE72DC	[129]
Fused filament fabrication (FFF)		Providing viable and cost-effective solutions for design validations, the fabricated production with	Poor finish, geometrical fits and tolerances, anisotropy, in-printing errors, and limited mechanical	Thermoplastic elastomers (TPE), FilaFlex	[133]

		high-performance, materials and printing flexibilities	strength	Acrylonitrile styrene acrylate thermoplastic filament	[135]
				Printer filament polylactic acid or acrylonitrile butadiene styrene (PLA or ABS)	[136]
				Thermoreversible Diels–Alder DA polymers	[138]
				Thermoplastic elastomers (TPE) filament	[139]
				Polyurethane Thermoplastic 95 (TPU 95A), a low-friction polyurethane thermoplastic	[140]
Inkjet Printing		Mask-less non-contact deposition technique, rapid mass productions, high levels of production accuracy, arbitrary geometries, low cost	The nozzle is easily clogged	Silver ink	[143]
				Flexible silicone rubber, Galinstan, copper	[144]
				3 wt% carbon black powder, 26 wt% silicone polyglucoside dispersant, and a siloxane solvent	[145]
				Resin	[146]
Direct writing (DIW)		Convenient and easy operate, rapidly pattern 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)	[149]
				Electrically insulating silicone and an ionically conductive hydrogel	[150]

Subsequently, as the primary stems from 3D printing, the 4-dimensional (4D) printing is up and coming appearing due to the programming of physical and biological materials, which is the key of the technology.[152] The fourth dimension means that the objects printed can change structures over time, including shape, physical property, functionality, etc. That is when objects exposed to external stimuli (such as thermal, photosensitivity, moisture, electronic, magnetics, chemical, light, mechanical, PH, pneumatic or another energy source), the objects' structures change.[153,154] This feature has an important challenge for the choice of materials. The SRMs that change with external stimuli occupy an important place in the field, and SRMs usually divide 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, laser beam), magnetic field, electric field, etc. can be classified as external trigger. Controllable or voluntary chemical reaction is classified as an internal stimuli-responsive system.[155] In addition, SMMs are a kind of materials that undergo reversible deformation due to martensitic transformation, they can usually be divided into SMAs, SMPs, Shape Memory Composites (SMCs), and Shape Memory Hybrids (SMHs) in some research. These materials can change over time when the external environment changes, 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 elastomer,[156] hydrogel,[157] and SMP combine with other functional materials.[158,159] There is also some research on multi responsive soft robots which are fabricated by 4D printing. Jin et al. fabricated crystalline SMP based single-component soft robot which is performance 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 proved to be used in reconfigurable, and remotely actuated soft robots. However, to obtain a reconfigurable behavior of the system, multiple -stimuli need to be present simultaneously.[161] In addition, some research on soft robotics used 4D printing technology as well. These soft robots have good application prospects in biomedical field.[162-164]

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

2.4 Others

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

In order 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 by a hybrid fabrication technology inspired from the octopus. The integrated design strategy including 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 research are helpful for the programmable assembly of the multiple materials in a single body, providing an idea worth learning from.[170]

Table 2. The advantages and disadvantages of fabrication approaches 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, need to remove bubbles generated during the molding process as well
Etching	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 need certain requirements for the environment
Laser		
Soft lithography		
3D printing	High quality, low cost, environmentally and ecologically favorable	The materials that can be printed have limitations.
4D printing		

In this chapter, some approaches used to prepare soft robots are classified and introduced (in **Tab. 2**), some typical examples are used to explain 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 the soft robot is a necessary step for the soft robot to exert its functional characteristics. This chapter introduces the driving strategies of the soft robots. We divide it into two major directions: 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 the soft robot. The shape, structure, and distribution position of the actuators determine the functional characteristics of the soft robots to some extent. In the previous review of actuators, El-Atab et al. reviewed the different soft actuation methodologies and their various applications in soft robotics.[171] Marchese et al. reviewed the soft robotic actuators from two aspects, the operating principles and morphologies. The morphologies including the design and the fabrication of three different soft fluid elastomer body segments: ribbed, cylindrical, and pleated.[172] This section mainly summarizes the types of actuators, including soft pneumatic actuators (SPAs), elastomer actuators (EAs), and others.

Regarding materials-based driving strategies, the actuation of the soft robots is realized by driving deformation under the stimulation of the external environment (such as thermal, magnetic, electric, light, etc.). This section introduces the indirect drive material elastomer, 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] introduction actuators is one of the most common driving strategies in soft robotics, which allows soft robots 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 as well as delicate applications including surgery and nano-/micro-materials fabrication.[176-178] In recent researches, Soft Pneumatic Actuators (SPAs) and Elastomeric Actuators (EAs) are the prevalent actuation strategies for driving soft robots.[32] This section mainly summarizes these two aspects, and at the end of the section, some other actuator types are also described.

3.1.1 Soft pneumatic actuator-based driving strategy

The soft actuator has become a vital strategy to drive the soft robot because of its ingenious design structure and flexible degree of freedom. Conventional soft actuators have shortcomings in robustness, repeatability, controllability, and force output performance, etc. Soft pneumatic actuators (SPAs) can solve the above 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, therefore the SPAs are inherently soft and vastly customizable. Different forms of SPAs will be used in different occasions. Sun et al. presented the characterizations of two different types of silicone rubber-based SPAs: bending and rotary. The bending movement of the bending SPA is like the movement of a human finger and can be constructed in a bundle to form an artificial muscle that contracts upon inflation. While the rotating SPA can be used as an active hinge for small robotic equipment. Through the design and analysis of the SPAs with origami shell reinforcement, Paez et al. found that when the shell provides reinforcement, the performance of the bending module is significantly improved. With the help of the shell, the bending module can 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 silicone elastomer with polyaramid fiber to fabricate a bellow-like gripper which can pick up a wine glass either from the inside or the outside by bending bidirectionally using positive or negative pressure. The gripper increases the tear resistance and have self-healing ability through small punctures.[182] Yi et al. proposed a pneumatic soft linear actuator Fiber-reinforced Origamic Robotic Actuator (FORA). The design and fabrication of FORA is shown in **Figure 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 combine this new origamic chamber with a reinforced fiber mesh to achieve high traction (over 150N) and large contraction motion (over 50%) under low input pressure (100 kPa). And through the developed quasi-static analysis model 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 elastomer led to the development of the design and mechanical properties of the soft robotics.[184]

To improve efficiency of the soft actuator, iterative optimization through simulation to design the soft actuators that meets the specified performance indicators and geometric constraints.[185] Moseley et al. applied 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 respectively. Regarding to the simulation and experimental results of linear SPAs, at low and medium pressure, the predicted results of various dimensions in displacement testing are consistent with the experimental values. And the results of linear SPA's block-force in FEM and experiment are similar. When the pressure is less than 30 kPa, the simulations show higher forces than the experiments, before a sharp increase in force is observed in both the experiments and simulations (in **Figure 4b**). The data of bending angle and blocked-force of bending SPAs shown that the simulations match the experimental results at low pressure, and capture the experimental trends at high pressure where significant rotation occurs (in **Figure 4c**). These analysis results show that the complex effects of SPA can be analyzed, so that the shape and design of actuator 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 design and preparation efficiency of SPAs.[186] They applied finite elements simulation or related software analysis to design SPAs in advance, and then prepare real soft robots to meet the specific performance and constraints. Chen et al. designed a SPA that is bionic human esophageal peristalsis. Multi-layer inflatable chambers are regularly embedded and distributed along the axis of the food passage, located in the center of the actuator. They first used finite element analysis and simulation to help structural design, and then prepared molds for silicon rubber pouring 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 is mainly determined by the local cavity.[187]

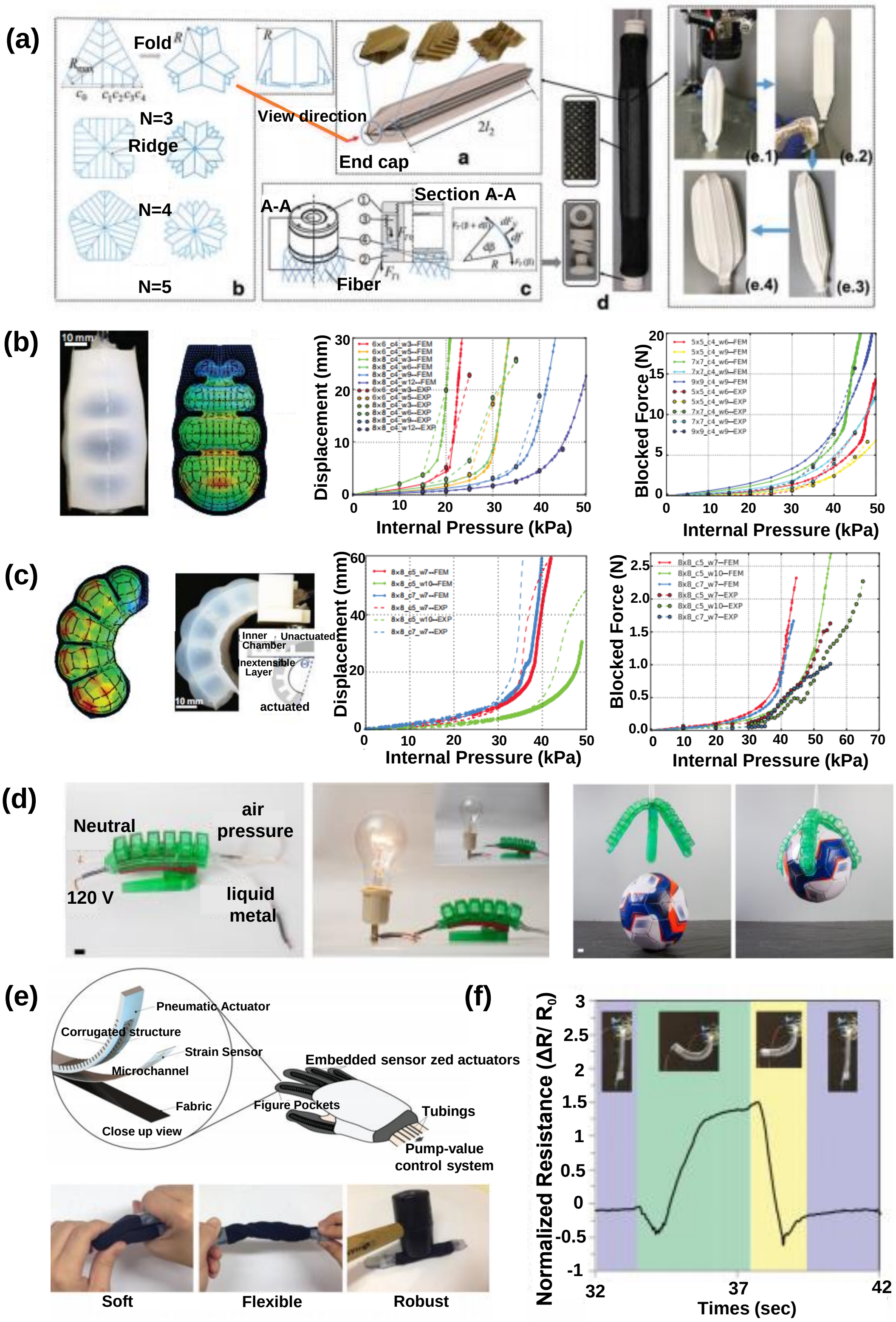


Figure 4. (a) The design and fabrication process of FORA. These figures show the concept of the origami chamber with basic origami patterns, schematic of End caps of origami chamber with different number of ridges, schematic design of the connection fittings, the fabricated prototype of FOR A, and fabrication process of the origami

chamber, respectively.[183] Copyright 2018, Mary Ann Liebert, Inc.. (b) Finite element analysis of linear SPA. Simulation and experimental comparison results under various dimensions in displacement testing and blocked-force testing. (c) Finite element analysis of bending SPA. Simulation and experimental comparison results under various dimensions in displacement testing and blocked-force testing.[186] Copyright 2016, WILEY-VCH. (d) The 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, American Chemical Society. (e) The picture of applying the actuator in the glove to facilitate data collection and the data diagram of the corresponding electrical signal when the actuator is bent. And the pictures well shown that the actuator has the characteristics of soft, flexible, and robust. (f) Electrical signal corresponding to one actuator bending.[189] Copyright 2016, WILEY-VCH.

In addition to the above descriptions, some soft robots are designed to combine SPAs with other technologies, devices, or mechanisms to prepare a new type of multi-functional and expandable comprehensive soft robots. Gomez et al. proposed an elastomer system with a vat photo-polymerizable self-healing property that can be elongated ten times than original. The self-healing elastomer is printed by 3D printing technology and combined with functional liquid metal to fabricate a multi-functional soft robot through modular assembly that can be used for both grasping and pneumatic light switch (in **Figure 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 realizes bending by connecting air source. The strain sensor achieves stretchability and flexibility by coating a thin layer of screen-printed silver nanoparticles on an elastic substrate while maintaining excellent electrical conductivity (at ≈8 Ω sq $^{-1}$) (in **Figure**

4e). This method has broad application prospects in the field of rehabilitation sensing and the proposed strategy has an important inspiration for the combination of soft actuators and other functional devices. The electrical signal generated when the actuator is bent is shown in **Figure 4f**.[189] Xu et al. built a soft robot that combines pneumatic actuator and jamming mechanisms. And through the finite element analysis and optimization of 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 has the characteristics of variable stiffness and can withstand the variable stiffness of 0.025-0.138 N/ mm, and the designed coupling mechanism can 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 preparing SPAs. In addition, SPAs combine with other technologies, devices, or mechanisms to prepare a multi-functional soft robots will also become the development trend in the SPAs field of soft robots. However, SPAs usually require numerous pneumatic accessories which are difficult to miniaturize. The miniaturization of the soft pneumatic actuator will also be one of the directions of the next research.

3.1.2 Elastomeric actuator-based driving strategy

In this section, we mainly introduce two types of EAs, fluidic elastomer actuators

(FEAs) and dielectric elastomer actuators (DEAs).

FEAs are actuators composed of low durometer rubber and is 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 used 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. It is the combination of the relative inextensibility of stress and strain that produces the deformation of the elastomer materials. FEAs can be powered pneumatically or hydraulically.[172,191]

Some research has been carried out to reduce elastomer strain on the outer layer of the actuator.[77,102] Mosadegh et al. designed a new pneu-nets that reduces the amount of gas needed for inflation and increases the speed of actuation as well (in **Figure 5a**). The designed actuator can be bent from linear to standard quasi circle in only 50 ms in **Figure 5b** (ΔP=345 kPa). When fully inflated, the volume change of the chamber designed in this paper is relatively small, which makes the strain level of the material under the maximum driving amplitude relatively low, and the fatigue fracture and failure rate will also be reduced. Through the circle test, the performance of the actuator will not change significantly even after running more than one million times (in **Figure 5c**).[102] The fluid actuator that realizes a large amplitude motion generally requires a large amount of energy supply, and the operating speed and compactness of the actuators are limited. Overvelde et al. built a fluid actuator by combining the 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 the SPA soft robots, the 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) (in **Figure 5d**). The FEA array can realize anguilliform locomotion. They developed an underwater untethered anguilliform swimming robot, and proposed the design and manufacture of fiber-reinforced bidirectional bending finite element. By measuring the bending angle of the FEA array dynamically loaded in water, it is proved that the performance of FEA depends on the driving signal and the position of FEA. Comparing the three-dimensional simulation results of the finite element method, it is concluded that the designed FEA array has a good experimental effect (in **Figure 5e and 5f**).[193] Moser et al. set out to simplify the design process of soft robots with incompressible fluid, inextensible fibers, and extensible elastomers by capturing interactions as pure geometric relationships. This can predict the direction of deformation of the soft robots in advance and determine a feasible topology that meets a series of motion requirements for single and parallel actuators configurations.[194] Galloway et al. designed and manufactured a fiber-reinforced soft actuator whose bending radius and bending axis can be mechanically programmed. Experiments have 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 can 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 is composed of soft rubber with fluid elastomer actuators distributed in it to provide fluid energy. This research proves that the research method of planning and control based on dynamic models can be applied in the design and development of soft robots.[196]

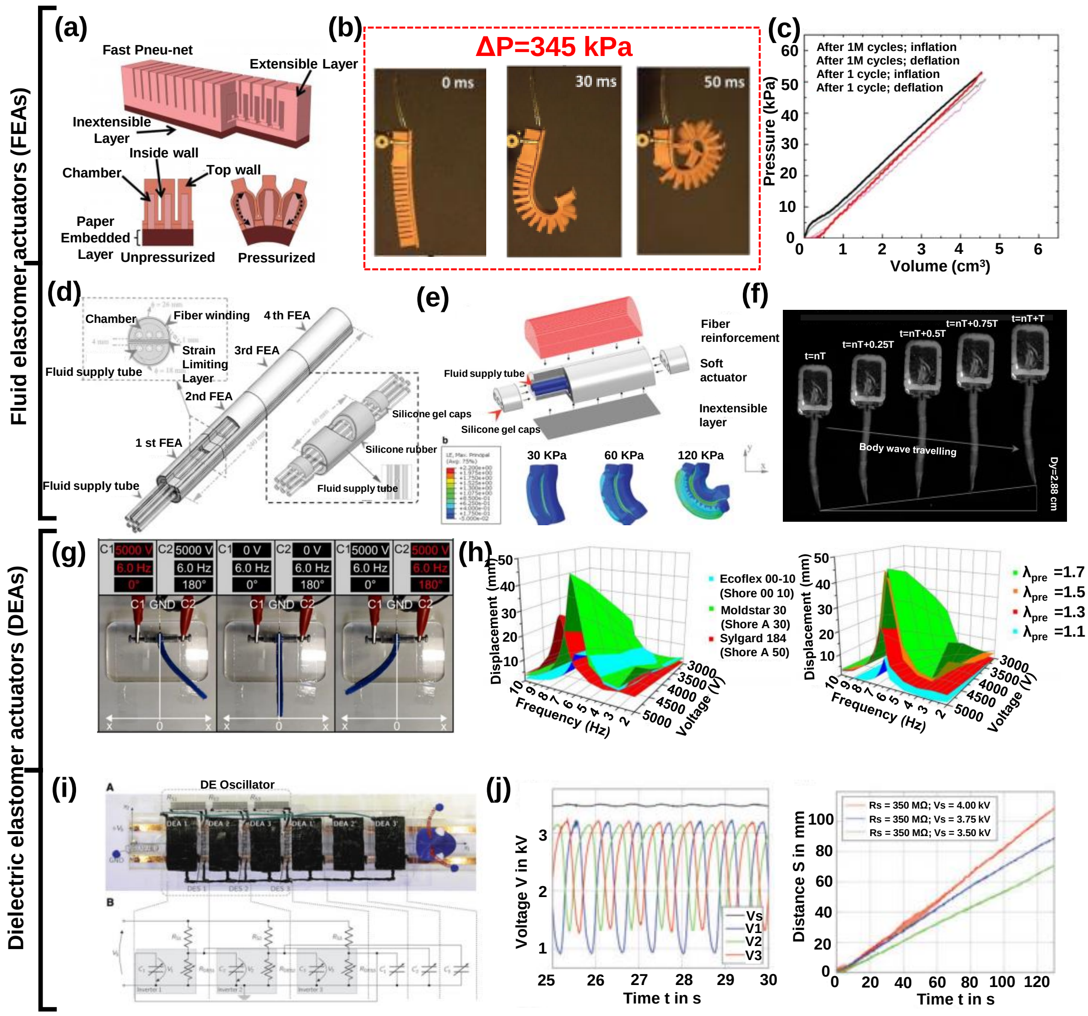


Figure 5 (a) The schematic diagram of the designed actuator. (b) High-speed video time-lapse image under 345 kPa pressure. (c) Fatigue test of actuator under one million cycles.[102] Copyright 2014, WILEY-VCH. (d) Structure of the FEA array. (e) The 3D finite element method model and simulation results 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 (Ecoflflex 00-10, Moldstar 30, Sylgard 184) and different pre-stretch (λpre = 1.1, 1.3, 1.5, 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 the position of the soft robot under different supply voltages during the experiment. [200] Copyright 2017, Mary Ann Liebert.

Converting types of natural motions into engineering motions is a core issue of preparing soft robotics by biomimetic phenomena or functional characteristics of natural organisms. The Dielectric Elastomer (DE) with the functional characteristics of artificial muscles has the properties of softness, light weight, and large stroke and can exhibit large strains (10%-50%) and moderate stress (around 100 kPa), so it has a good application prospect in driving multifunctional bionic mechanisms. DEAs used DE to directly control the drive of a soft robot 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 is driven by an antagonistic working DEAs artificial muscle pair. The existence of DEAs makes the soft robot 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 the research the various parameters to achieve the optimal design of the actuator performance. The real-time displacement measured by the prepared soft robot is shown in **Figure 5g.** The soft robot in this experiment successfully tested the real-time displacement under static and dynamic conditions. The **Figure 5h** shows the displacement of the soft robot under different voltages and frequencies under three different silicon body materials (Ecoflflex 00-10, Moldstar 30, Sylgard 184) and four different pre-stretching (λpre = 1.1, 1.3, 1.5, 1.7) of the DEA silicone membranes with Moldstar 30 as silicone body material. The system designed by this research will have the potential value of important applications in the fish tail design of the bionic fish soft robot in the future.[198] When it comes to bionic fish tail, Berlinger et al. designed a fin-liked DEA that can 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. The structure diagram of the designed bionic crawling soft robot is shown in **Figure 5i**. The prepared soft robot uses a dielectric elastomer oscillator (DEO) to change its electrical resistance and switch charge flow on and off on a mechanical deformation. The soft robot will automatically generate all the signals needed to drive its DEAs after receiving the external DC voltage, and convert the in-plane electromechanical oscillations into crawling motion (in **Figure 5j**). The movement of each DEA muscle is controlled by the mechanical strain of adjacent muscles. Research shows that designing a bionic soft robot with soft actuator and charge control device is a feasible and promising research direction.[200]

Nguyen et al. prepared a hexapod-driving walking soft robot inspired from insect. A 3D printing method is 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 can 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 is subjected to voltage, the membrane expands, the volume of air increases, and the buoyancy force acting on the robot increases. At the same time, water is sprayed from the body of the robot, which can 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 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. Hajiesmaili et al. introduced in detail the characteristics, design, operation, and influencing factors of DEAs from the perspective of physics, providing a theoretical basis for the design of DEAs that are more suitable for the field of soft robotics. Improving the uniformity of the motor and the reliability of the actuator, and developing higher dielectrics are the areas where DEAs are used in soft robotics in the future.[203]

In summary, this section introduces two elastomer actuators, FEAs and DEAs. FEAs can be actuated pneumatically or hydraulically and DEAs are mainly used in the driving device of the 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 two types of common actuators above, there are some other types of actuators. These actuators have researches on the functional characteristics of bionic natural organisms, research on the mutual coupling of multiple actuators, and research on the realization of the miniaturization of the actuators, etc.

Inspired by osmotic function of plants, Must et al. designed a tendril-like soft robot based on the 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 (1.3V). And they demonstrated the reversible hardening (~5 times increase) and driving (~500-degree rotation) of a tension-like soft robot (diameter ~1mm). This driving strategy and the characteristics of being based on biocompatible materials and being able to be used under 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 is composed of a dielectric elastomer actuator with driving deformation characteristics, and the two paper-based feet are composed of electroadhesive actuators. This soft robot can deform through alternate expansion/contraction of the body and realize movement through the adhesion/detachment of two feet. Strong electroadhesion ensures stable movement, and the large voltage induced deformation and fast response of the robotic body leads to a velocity of 0.02 body length/s. This paper also analyzes the body deformation of the soft robot by finite element analysis and proves that the soft robot is more susceptible to the influence of the dissipation process.[205]

To miniaturize the prepared soft robots, Keya et al. used natural proteins as actuator and control system to prepare the molecular robots. The results show that developing actuators with multiple embedded characteristics provides a feasible way to miniaturize the 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 kind of soft robots mainly make improvements and breakthroughs from the aspect of applied materials. And 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 into 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, so that it can be actuated directly through changes in the environment. This section mainly introduces from elastomer and SRMs. Since 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, the elastomer is one of the most used materials to prepare soft robotics. The elastomer itself does not have the characteristics of being driven in response to external environmental conditions, usually by adding functional particles that response to environment in the elastomer to achieve the driven of whole soft materials 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 easy fabrication process, low toxicity, excellent mechanical properties, and silicone rubber material is a basic material with good comprehensive performance.[207,208] In some representative studies, the functional particles added to the elastomer are 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 and so on.

The research on elastomers that respond to the external magnetic field and electric field are as follows. Venkiteswaran et al. combined silicone rubber and magnetic power to prepare various types of soft robotic grippers (tail gripper, flower gripper, Millipede robot) that can actuate in response to external magnetic field.[209] Choi et al. proposed a gripper skin with reversible and hardness variable properties which is based on shape-adaptive magnetorheological elastomers. The gripper skin is attached to a robot gripper, and the composite of SMRE are silicon oil, silicone rubber, and carbonyl iron particles (CIPs) (in **Figure 6a**). They found that the CIPs contents determine the mechanical property of the SMRE-based skin. The gripper with SMRE-based skin can response to magnetic to achieve grasp and release various types of target objects (a cylinder, cuboid, and triangular prism) easily without damage the objects. When the applied magnetic field is 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 **Figure 6b**.[210] Nasab et al.[211] and He et al.[212] fabricated rigid tunable elastomer strips and soft tubular actuators respectively which are both response to electrical current. The rigid tunable strips are fabricated by conductive propylene-based elastomer and used as the ligaments. The stiffness of the ligament changes under the electrical current. The soft tubular actuator fabricated by liquid crystal elastomer exhibits multidirectional bending as well as large homogenous contraction (~ 40%) under the electric. These characteristics make them response to current to achieve actuate.

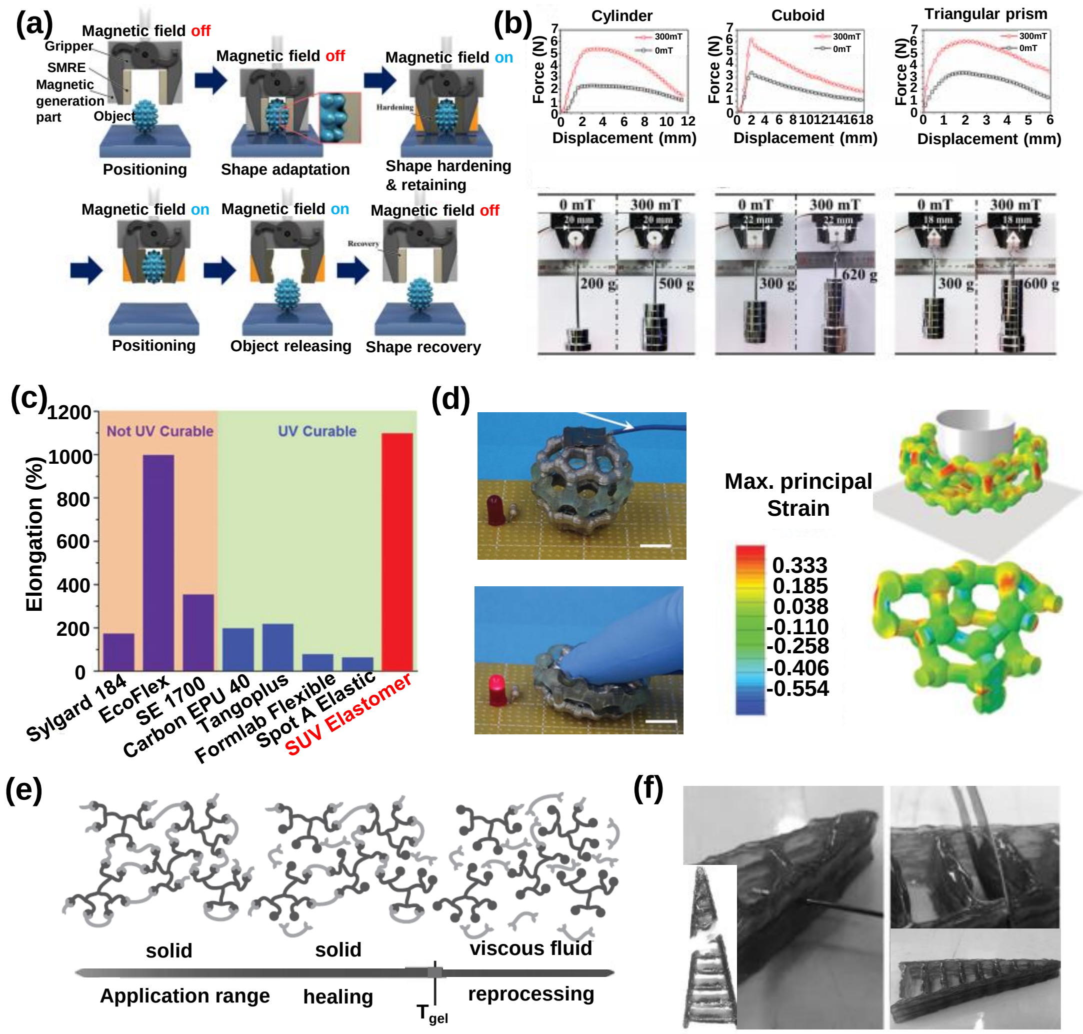


Figure 6. (a) Operation scene of parallel jaw gripper with SMRE-based skin. (b) Data graph and schematic diagrams of grasping force for grasping objects with different shapes.[210] Copyright 2020, American Chemical Society. (c) Elongation data graph of

different elastomers. (d) The soft robot is used as the conductive bucky ball to light up the LED picture and the finite element simulation diagram when the conductive bucky ball is under pressure. [215] Copyright 2017, WILEY-VCH. (e) Schematic diagram of the prepared self-healing software material reversibly cross-linked through DA bond. (f) The pictures of damaged soft robot and after recovery.[138] Copyright 2019, Mary Ann Liebert, Inc.

In addition to above common elastomer, some novel elastomer materials and interesting functions are proposed. Zhou et al. fabricated a novel soft robotic by using a memory foam sheet and a patterned elastomeric layer to pick up various objects.[213] UV-curable elastomers are also used to prepare novel soft robots to achieve actuate. 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 can enhance the activation and bending movement of the gripper.[214] Patel et al. used similar method to fabricate soft actuator by using stretchable UV elastomer resin. Compared with not UV curable silicone rubber and commercially available UV curable elastomers, the highly stretchable and UV curable (SUV) elastomer they proposed can be stretched by up to 1100% (more than five times the elongation at break of the commercial UV curable elastomers) and can be used as a gripper with outstanding performance in the grasping objects (in **Figure 6c**). This SUV elastomer material can be used as a conductive bucky ball for electric switches as well. The picture and finite element simulation of the LED light when the soft robot is under pressure are shown in **Figure 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 get the attention of researchers. The so-called self-healing property is that objects can recover completely from macroscopic damage over time. Roels et al. used thermal-reversible Diels-Alder (DA) to prepare a soft gripper with self-healing property (in **Figure 6e**). We restored the 3D printed fingers when they were damaged to varying degrees (fatal and not fatal), and the results showed that the injured fingers can repair themselves with only a small visual scar (in **Figure 6f**). The usage of the FFF 3D technology provides the idea for similar soft robots' preparation in the future, making the prepared soft robots more freedom and less manual effort. And the prepared soft robot with self-healing performance has an important application prospect in some fields.[138]

In summary, this section introduces the response of adding various functional nanoparticles to the elastomer to achieve the 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 are 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 materials-based driving strategy

SRMs refer to the realization of perceivable and responsive materials to external environment through the coordination of various functions within the materials, and there are usually many types of such 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 polymer, liquid crystal polymer and elastomer, azo-benzene, hydrogels, bio-hybrids).[55] Ube et al. reviewed photo mobile materials with crosslinked liquid-crystalline structures, which has great potential application value in the microactuators 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.).

Research on the response of the soft robotics to the external thermal environment, lower critical solution temperature (LCST) is an important concept. Realizing the driven of materials through the control of temperature whether reaches LCST, and poly (N-isopropylacrylamide) (pNIPAM) is usually used as a base material to response well to the external temperature changes.[220,221] To achieve the functional applications of the soft robots system 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] all used poly [N-isopropylacrylamide-co-acrylic acid] [p-NIPAM-AAc] as the main material, and adjust and control by adding magnetic-responsive Fe_2O_3 to achieve soft robotic system response both thermal and magnetic. In addition to the research of PNIPAM-AAc as the main material to response thermal and magnetic, Kobayashi et al. combined high swelling poly (oligoethylene glycol methyl ether methacrylate) (P(OEGMA-DSDMA)) and low swelling poly (acrylamide-N, N′-bis (acyloyl) cystamine) (P(AAm-BAC)) with magnetic Fe_2O_3 NPs to fabricate soft gripper that can be used of stimuli-responsive biodegradable soft-gripping robots (in **Figure 7a**). The soft gripper moves under the action of the magnetic field, and realize the grasp and release soft cargo under the action of the thermal, the whole process is shown in **Figure 7b**. In addition, the prepared soft gripper is based on the comparison of ISO standards, and the results show that the gripper is simultaneously biocompatible and biodegradable, and the experiment has successfully proved that the soft gripper can be used for thermally actuatable drug patch applications. They also fabricated a range of thermally responsive self-folding structure by poly [oligo (ethylene glycol) methyl ether methacrylate] (POEGMA) gels that can be used as a gripper to response three kinds of temperatures.[224]

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

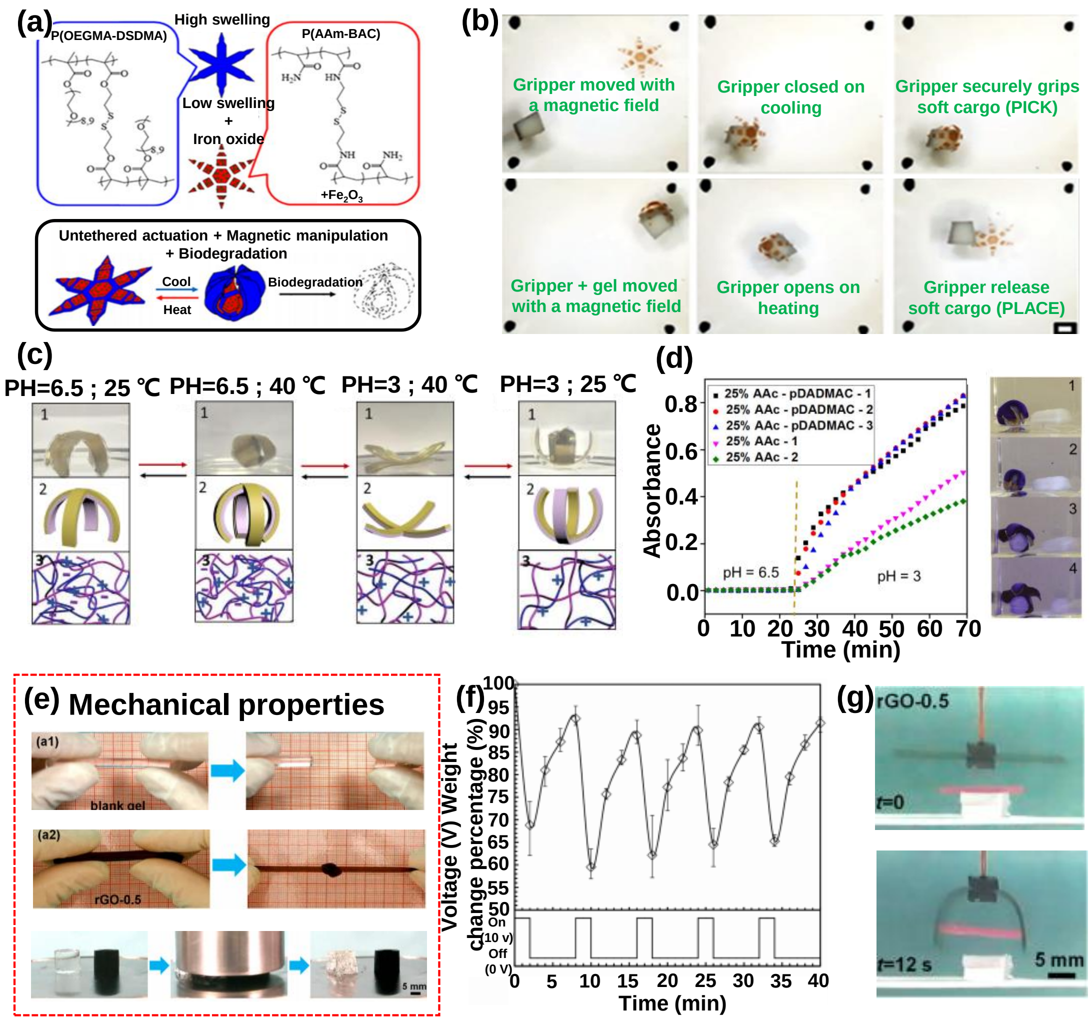


Figure 7. (a) Schematic diagram of the molecular composition and structure of the

preparation of the soft robot, and the prepared soft gripper operation process. (b) The whole process of soft cargo grasping and releasing by the soft gripper under the action of thermal field and magnetic field.[224] Copyright 2018, American Chemical Society. (c) The process of the soft gripper grasps and releases under the action of PH and temperature. (d) The release profiles and pictures of soft robot triggered by PH.[228] Copyright 2017, The Royal Society of Chemistry. (e) Mechanical properties of hydrogels. (f) Reversible deswelling/ swelling behaviors of rGO-0.5 hydrogel. (g) The response of the soft robot to the electric field. [231] Copyright 2017, American Chemical Society.

Other SRM materials used to prepare soft robotic can respond to electric simulation. Yang et al. used graphene oxide/poly (2-acrylamido-2-methylpropanesulfonic acid-co-acryla mide) (rGO/poly-(AMPS-co-AAm)) nanocomposite hydrogel to fabricate soft actuator. By comparing the blank gel with rGO-0.2, rGO-0.5 and rGO-1.0, the prepared hydrogel with rGO added with excellent mechanical properties (in **Figure 7e**). The fracture stress and the tensile fracture strain increase with the increase of rGO content. The fracture stress value rGO-1.0 is about four times that of the blank gel, and the tensile fracture strain of rGO-1.0 reaches 297.93%. When an electric field is applied for 2 mins, the hydrogel shrinks by 58-68% of its original state. After the electric field is removed, the hydrogel can be swelled again by immersing it in water for 6 mins. The prepared hydrogel exhibits rapid and reversible electro-response as well (in **Figure 7f**). The gripper prepared with rGO-0.5 hydrogel can grasp object with 15 mm efficiently (in **Figure 7g**).[231] Chen et al. embedded super-aligned carbon nanotube sheets into PDMS to fabricate a soft robot that can response to very low-driving direct current voltages to generate a remarkable bending actuation than the existing thermal actuators.[232] Davidson et al. combine dielectric elastomers with fast and highly efficient actuation characteristic 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 achieves 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] There is also early research that Zhou et al. prepared three kinds of grippers based on polymer MEMS that response to ion movement in an electric field, thermal, and electrochemical oxidation-reduction (redox) reaction, respectively. All these micro grippers can be used underwater with large deflections and require less power input. This work is of great significance for the design of grippers in response to various environmental factors underwater.[234]

Soft robots that respond to a magnetic field mainly add magnetic responsive particles to the materials to achieve magnetic field control. Common magnetic field-responsive particles including Fe_2O_3, Fe_3O_4, ferrite powder, NdFeB, NdPrFeB.[235-237] Ji et al. used digital light processing (DLP) 3D printing technology to fabricate a magnetic responsive soft robot by magnetic photosensitive resins incorporated Fe_3O_4 NPs. DLP 3D printing enables printed soft robot with complex architecture and excellent mechanical properties to achieve bending, deformation, cargo transformation.[236]

There is also interesting research on hydrogels. Yuk et al. used hydrogels to fabricate a soft robotic with six bending actuators to catch a live fish in water. The soft robotic has high-speed, high-force, and optically and sonically camouflaged in water. The soft robot with excellent mechanical properties so that it can maintain robustness and functionality when subjected to moderate stress.[238] Li et al. reported an interesting work that they fabricated a soft robot can walk in water on either flat or inclined surfaces and delivery objects through light and magnetic field driven shape changes. The materials they used and designed are embedding rigid and macroscopically aligned ferromagnetic nanowires that response to magnetic field into a soft photoactive hydrogel that respond to light. Through the theoretical description of the dual-response external energy input and experimental verification of the hydrogel's trajectory research, their work realized the programming and design of the soft robot to achieve response of light and magnet as expected.[239] Research conducted by Zhang et al. also suggested the conversion of light into mechanical work. 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, 980 nm), which has a broad application prospect in soft robot and bionic technology. [241]

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

3.2.3 Shape memory materials-based driving strategy

Shape memory materials (SMMs) usually exhibit changes in stiffness via phase transformations, this makes the SMMs to control the stiffness by controlling the SMMs' phase, and has great potential in the preparation of soft robotic.[246-248] The representatives of 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 few mm in length that can grasp a screw.[158] Behl et al. fabricated a gripper in a cross like manner by using PPD-PCL (75) ribbons. The gripper achieves grasping and release through temperature changes, and successfully grasps a penny.[249] At present, the main limitation of such system is that inherent softness leads to small actuation force. To make SMPs better use in grippers and grasp relatively large and various objects, it is necessary to improve the mechanical properties of the SMPs, such as employing SMPs composites with other functional materials.

SMPs have also made some progress in the research of responding to thermal, light, and magnetic etc. Therefore, these SMPs can prepare a soft robot that responds to the external environment. Hubbard et al. converted SPM planer sheets into 3D objects with controlled curvature. The sheets' surface ink pattern can absorb the infrared (IR) light to achieve localized heating. The drive of the materials can be reached when the increased temperature by absorption of IR is higher than the activation temperature.

The prepared soft robot can grab objects around 925 times its own weight, and has a certain application prospect for temperature control grabbing.[240] Ze et al. used two types of magnetic particles (NdFeB and Fe_3O_4) in an amorphous SMP matrix to fabricate soft robot that can response to magnetic field (in **Figure 8a**). Low-coercivity particles through magnetic inductive to make matrix system soft, and high-remanence particles which are reprogrammable magnetization profiles make the shape change when exposure magnetic fields. The soft robot integrates reprogrammable, untethered, fast, and reversible shape transformation and shape locking into one system. And the soft robot provides a wide range of applications in many fields.[250] Chen et al. fabricated a novel soft robot by SMP that can response to light and magnetic repeatable and sensitive (in **Figure 8b**). The material of soft robot based on biocompatible PCL/ TPU/ Fe_3O_4@ PDA which has the self-healing performance during the light illumination (in 120 s) with the efficiency reach to 90%.[251] Recently, Liu et al. applied semicrystalline poly (ethylene-co-vlnyl acetate) (EVA) involved with silver nanowires (AgNWs) to assemble complex 3D structure, multifunctional, and self-healing composite actuator by light welding. AgNW/ EVA composite can response quickly under the irradiation of light and exhibit good reusability characteristics. The strategy of incorporating photo-thermal responsive composite particles into SMPs to achieve response to light in this experiment has provided inspirations for preparing soft robots that respond to special conditions. And the excellent self-healing function displayed by the soft robot in this experiment provides a good direction for the future design of soft actuator used in exploration, medical rehabilitation, and military reconnaissance fields.[252] Pang et al, designed linear liquid crystal copolymer which the eutectic mesogens of azobenzene and phenyl benzoate self-organize into the smectic B phase. The fabricated liquid crystal copolymer combines 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) that can be used as a soft robot. The soft robot can response temperature sensitively and achieve accurate gripping, transportation, and release of a glass vial upon swelling underwater.[113]

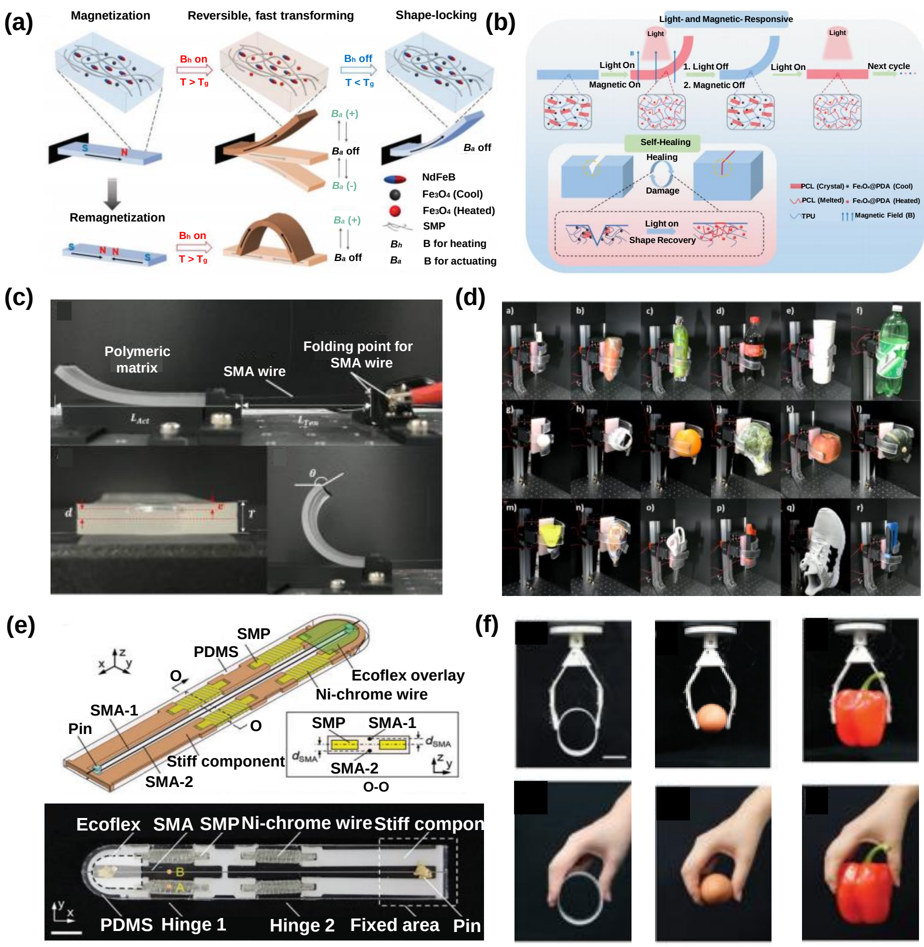


Figure 8. (a) Working machine of magnetic SMP.[250] Copyright 2019, WILEY-VCH. (b) Schematic diagram of light- and magnetic- responsive actuation and shape memory assisted self-healing.[251] Copyright 2021, The Royal Society of Chemistry. (c) SMA actuator and the bending deformation. (d) Schematic diagram 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 the human hand gripping the objects (low to high stiffness).[257] Copyright 2017, Mary Ann Liebert, Inc.

The SMA based soft robotics commonly used SMA wire embedded within the polymeric matrix, this method may cause the small stroke of the soft robot system to arouse the poor performance such as small bending angle and force versus other types of soft robots. To solve this phenomenon, Lee et al. used to 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 for the compact packaging of the driving SMA wires to increase bending angle and bending force (in **Figure 8c**). They applied actuator to prepare gripper that can grasp a large range of objects weighting up to 1.5 kg, and the maximum pulling force of the prepared gripper can reach to 30 N (in **Figure 8d**). The tendon design proposed significantly improved the performances of SMA based grippers.[254] The performance of SAM based actuator mainly depends on the configuration of the cross-section of the actuator. Rodriguez et al. fabricated an actuator with SMA wire 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 SMA-based actuator to make a soft robotic gripper which compared the two, the curved gripper can lift more than three times the weight of the object.[255]

There is also some research that imitate 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 the 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 by SMA wires (in **Figure 8e**). To achieve multiple postures, each finger has two hinges that can selectively change the stiffness of hinges and actuate relatively SMA wires. The prepared soft robot can adaptively grasp in low stiffness state and hold in high stiffness efficiently (in **Figure 8f**). Due to the stiffness changeable mechanism, the soft robot's maximum grasping force is increased to around 10 times.[257]

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

Table 3. The advantages and disadvantages of driven 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, twisting with the 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.
Materials-based Driving Strategies	Dielectric Elastomeric Actuators (DEAs)	Easy fabrication process, low toxicity, excellent mechanical properties.	Rely on the addition of nanoparticles to achieve driving.
	Elastomer	Can be directly driven by the environmental factors.	The speed of 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 within polymer matrix may cause stroke, which arouse poor performance.

In this chapter, we mainly introduce the soft robots driven strategies based on either actuator or materials (in **Tab. 3**). We introduce actuator-based driving strategies, and various common types of actuators used in soft robotic field. Also, the characteristics of different types of actuators and some related research published in recent years are described. Materials-based driving strategies was 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 from different response conditions. This chapter has important implications for the design of varied driving mode in soft robots in the future.

4. Applications

Due to the characteristics of the soft body, more degrees of freedom, and the ability to be designed to respond to external environment according to the functional requirements, soft robots have a vast probability of applications 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 medical and industrial related 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 robots design is an innovation in the field of robotics. This section is to explore the roles of artificial intelligence played in the preparation of soft robots and the functional applications of combining soft robots with artificial intelligence.

The introduction of machine learning is useful to soft robotics perception, design, and prediction of some characteristics. At first, Nakajima et al. believed that the various dynamics that driven soft materials can be efficiently used for machine learning. They used the soft silicone arm to confirm it and the results shown 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, chemical.) through the soft robots as the input parameters of machine learning, combined with machine learning algorithms (such as support vector machine (SVM), logistic regression, dimensional reduction, gradient boosting.) to realize the modeling of the unknown soft actuate system and human-robot interaction. Therefore, effective parameters input and efficient algorithm selection play the essential role to achieve the combination of soft robots and machine learning (in **Figure 9a**). With the development of current technology, the collection of soft robots signals mainly comes from electronic skin or soft devices with sensing equipment. Shin et al. reviewed the electronic skins and machine learning for intelligent soft robots.[260] In addition to the research mentioned in the review, there are also some other studies. Thuruthel et al. embedded a redundant and unstructured soft sensor topology in a soft actuator and used recurrent neural network (RNN) to achieve the perception of the soft robotics. They chose long short-term memory (LSTM) to train the sample data which is from the vision-based motion capture system due to the ease in training LSTM networks for long time-lag tasks. The fingertip's trajectory (blue line) and the predicted positions (red line) are shown in **Figure 9b**. About the force prediction of the fingertip, the prediction and error plot of the same test is shown in **Figure 9c**. The system exhibits a delay in detecting the cessation of contact, and the average error in other cases is around

0.05±0.06 N. The method in this work enables the development of force and deformation models for the 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 show that this method is feasible for realizing proprioception and is robust to common sensor failures.[262]

There is similar research that 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 a soft robot's 3D configuration 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 divided into three segments (S1, S2, and S3), the trained RNN well predicted the steady-state configuration of prepared soft arm even with hysteretic, non-monotonic feedback form the piezoresistive sensors. The validation results of random arm actuation are shown in **Figure 9d**. The photographs of the soft arms with four different kirigami sensors, ground truth and predicted configurations of soft arms poses, and ground truth and predicted configuration parameters versus time for three segments of the arms during random actuation cycles are shown respectively from top to bottom. Although this work provides the fundamental step toward deep learning to use in soft robotics' 3D configuration, the closed-loop feedback control system provided by this work has laid 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 is spray coated piezoresistive sensing layer on a latex membrane. They designed an adaptive controller to track a desired degree of curvature trajectory, and both low-frequency and high-frequency target trajectories can achieve satisfactory curvature tracking.[264] The information theory and machine learning will play a huge role in bringing soft robots to human-like performance levels.

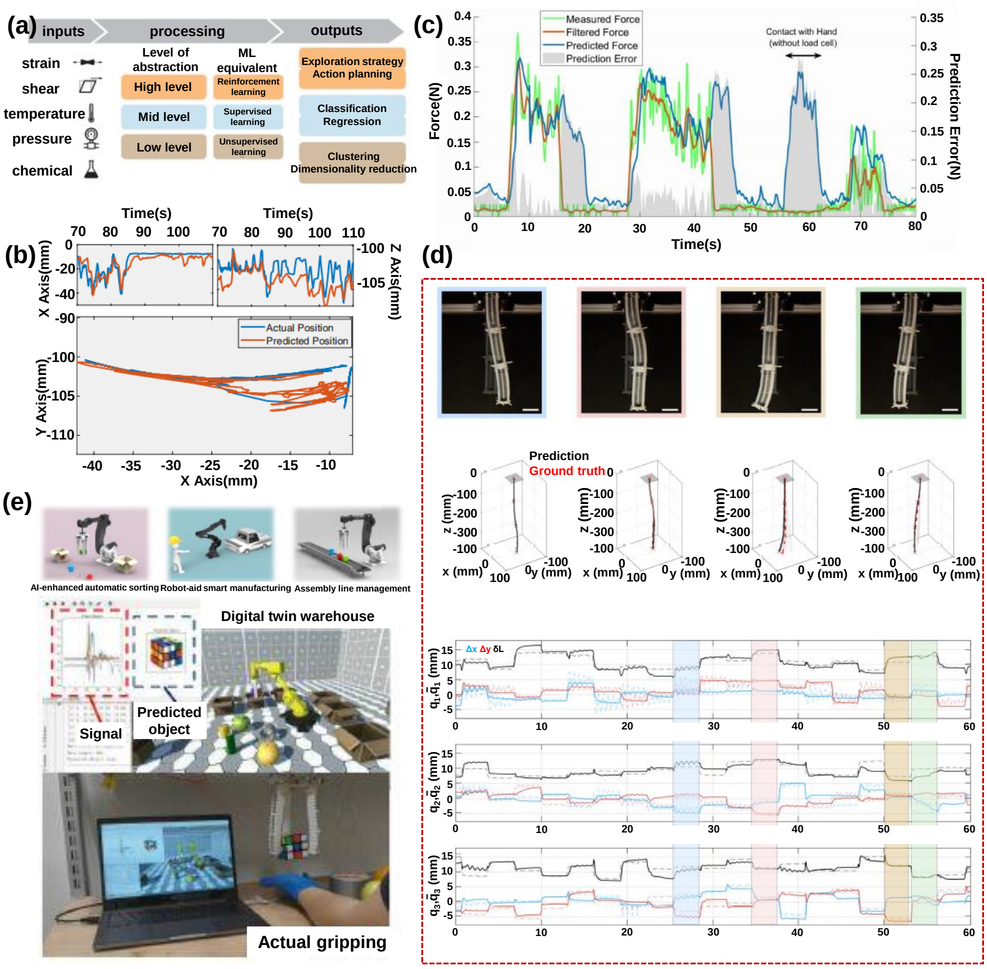


Figure 9. (a) Machine learning technology used to process raw sensory information, different levels of abstraction to help robot perception and action planning.[259] Copyright 2018, John Wiley and Sons. (b) Predicted motions of the fingertips with cPDMS sensors. (c) The force prediction at the fingertip.[261] Copyright 2019, The

American Association for the Advancement of Science. (d) The validation results on random arm actuation. [263] Copyright 2020, IEEE. (e) The 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.

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

In summary, one of the major difficulties of controlling soft robotic system 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 field has also shown excellent results. 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 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 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] hydrogel,[276,277] conditional response materials,[278-280] etc. Utilizing the deformation characteristics of these materials in the 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 surgeries,[280] drug delivery,[281] diagnosis of various disease and conditions,[282] rehabilitation,[283] and treatment in the 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 various directions that mentioned above in biomedical research, traditional and novel soft materials as well as different actuation strategies. They also discussed approaches and applications in the biomedical field in the future.[285] In addition, it is important for the soft robot to effectively heal the wound and not cause any damage to the surrounding soft tissue in the process, and this is also one of the difficult problems that needed to be solved.[286-288] Regarding the preparation technology of soft robots used in medical applications, in addition to some 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 medical field. Hann et al. reviewed 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 the inspiration of the functional characteristics of organisms. For example, the soft robots with a bionic octopus, 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 operations (in **Figure 10a**). However, the large size of the soft robot manipulator makes the operation limited during the surgery process, which will be improved in future research.[290,291] Joyee et al. fabricated a multi-material soft robot inspired by inchworm. The soft robot has a magnetic particle-polymer composites body which is fabricated by 3D printing technology. The soft robot can be used in drug delivery field due to the reservoir can store liquid drug and robot can release the drug once it reaches the target (in **Figure 10b**).[281] It was also inspired by worm, Tang et al. fabricated a DNA robot which is super-soft and super-elastic magnetic hydrogel based. The DNA robot exhibits shear-thinning, cyclic strain, and biocompatibility properties. The robot can complete a series of complex magnetically-driven movement and successfully works as a vehicle to deliver cells in confined space by virtue of the 3D porous networked structure. The schematic diagram of soft robot during the turning locomotion and the drug delivery in the human lungs are shown in **Figure 10c**.[292] Xu et al. fabricated a tissue-engineered transformable soft robot inspired by swimming whales that can be actuated by a muscular tail fin. The soft robot has the unprecedented controllability and responsiveness, and it can be applied as a cargo carrier for programmed delivery of chemotherapeutic agents to selectively eradicate cancer cells (in **Figure 10d**).[278]

In recent research, Lindenroth et al. first fabricated a fluidic soft robot that comprised of six embedded fluid actuators to translate and rotate of the needle as well as adapt stiffness in the coupling between needle and ear canal. They developed a vision system for tracking and positioning, thereby achieving safe needle insertion and reducing needle movement. The soft robot was successfully used in intratympanic steroid injection.[284] The above situation is attributed to the movement of the soft robot in a non-confined space. The application of the soft robotics in the medical field sometimes affects the motion of the robot due to the fluid-filled confined spaces. Ren et al. broke through the motion of the previously prepared soft robot that is suitable for dry environment.[293] They proposed a 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 tend to align soft robots' directions along with the external magnetic field to achieve the deformation of soft robots. Applying different external magnetic field makes different deformation modes to adapt different environments. The prepared soft robot is expected to be applied in the confined space filled with fluid in the human body in the future (in **Figure 10e**).[279] Some of the above-mentioned research is that the prepared soft robots have certain application prospects in the medical field, and 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 can support the cardiac output of the failing pig heart. Through the practical experiments proved that six pigs suffered from heart failure through drug treatment, making their heart failure to 45% of the basic level. After applying the soft robotic device, the heart function recovered to 97% of the pre-medicine treatment (in **Figure 10f**). [294]

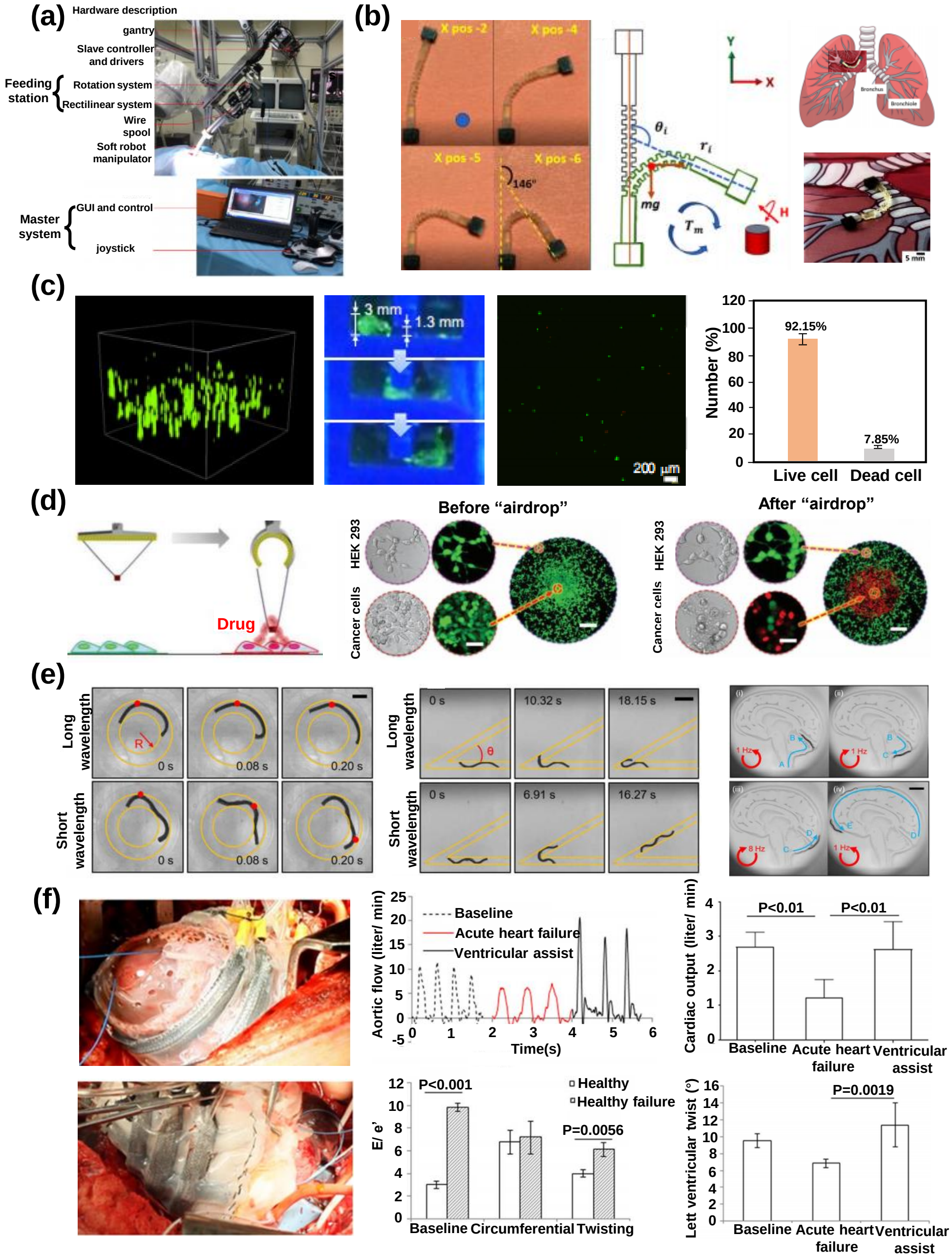


Figure 10. (a) The over view of the soft robot surgical system.[290] Copyright 2016, Springer. (b) An example of the turning locomotion of the soft robot inspired by inchworm, the displacement of the front legs on the x, y axis and the corresponding deflection angle, as well as the schematic diagram of the motion in the human lung.[281] Copyright 2020, Elsevier. (c) The DNA robot as a vehicle for cell delivery. The pictures from left to right represent the multi-layered cells cultured in a 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 cells 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 is manipulated in the phantom that simulates the brain aqueduct by adjusting the magnetic rotation frequency.[279] Copyright 2021, Publisher. (f) The 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.

In summary, in this chapter on the application of soft robots in the medical field, we introduce some predecessors’ reviews on this field. Then we described in detail some examples of the application of bionic soft robots in the medical field, which will inspire researchers to some extent. Finally, we reviewed some recent high-quality related articles. In short, the application of soft robots in medical field is currently a research stage, and further exploration and research are needed 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, light, etc.) in order to convert it into an electronic signal. The combination of specific sensors and soft robotics can realize the signal output of specified physical characteristics, which makes the 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 the field. They specifically introduced the developments in all aspects of sensing including proprioception, tactile sensing, sensing morphology, and sensor configuration.[295] This chapter mainly introduces sensor design and recent research progress.

The design structure and the selected material will directly affect the role of the sensor in the soft robot. And the tactile sensor is a key challenge in soft robots' development due to its limited flexibility and deformability. To solve the flexibility of the sensors that used in the soft robotics, the usage of conductive thermoplastic elastomer (CTPE) plays an essential role. The CTPE is a thermoplastic elastic matrix that is homogeneously mixed with carbon black powder under high pressure and temperature. Integrating CTPE in the software part of the robot will not change the mechanical performance of the overall system. The excellent extension characteristics of CTPE enable it to fully extend in the soft part without causing damage to the sensor.[296,297] Compared with strain gauge,[298] ionic liquid sensors,[299,300] ZnO nanowire films,[301] graphene foam[302] and silver nanocomposite,[303] CTPE[297,304] has 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 sensor implementation. The framework and schematic illustration of soft tactile sensing of objects are shown in **Figure 11a**. The construction of the theoretical framework has important guiding significance for the sensor of soft robotics to identify the specified parameters of target objects. They also applied 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 fewer sensor elements to provide more grasped object deformation information. This research allows the robot to identify grasped objects to enable improved the gripping and manipulation performance. It has important reference significance for the follow-up related research.[305] In terms of a tactile sensor, Yang et al. proposed an embedded sensing solution that they inserted a pair of optical fibers in the structural cavity of the soft robotic fingers so that the optical fibers will not affect fingers' adaptive performance, and the prepared soft robotic fingers have the properties of exceptional adaptation in all directions.

The electrical signal output by the sensor has an important meaning of analysis of object characteristics. Comparing actual object properties with sensor estimated properties, an object sorting task and identified sectional diameters of 94% objects within the ±6mm error and measured 80% of the structural strains within ±0.1mm/mm error (in **Figure 11b**). This research opens the doors for the scalable and adaptive physical interactions in the unstructured environment of the soft robotic field.[306]

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

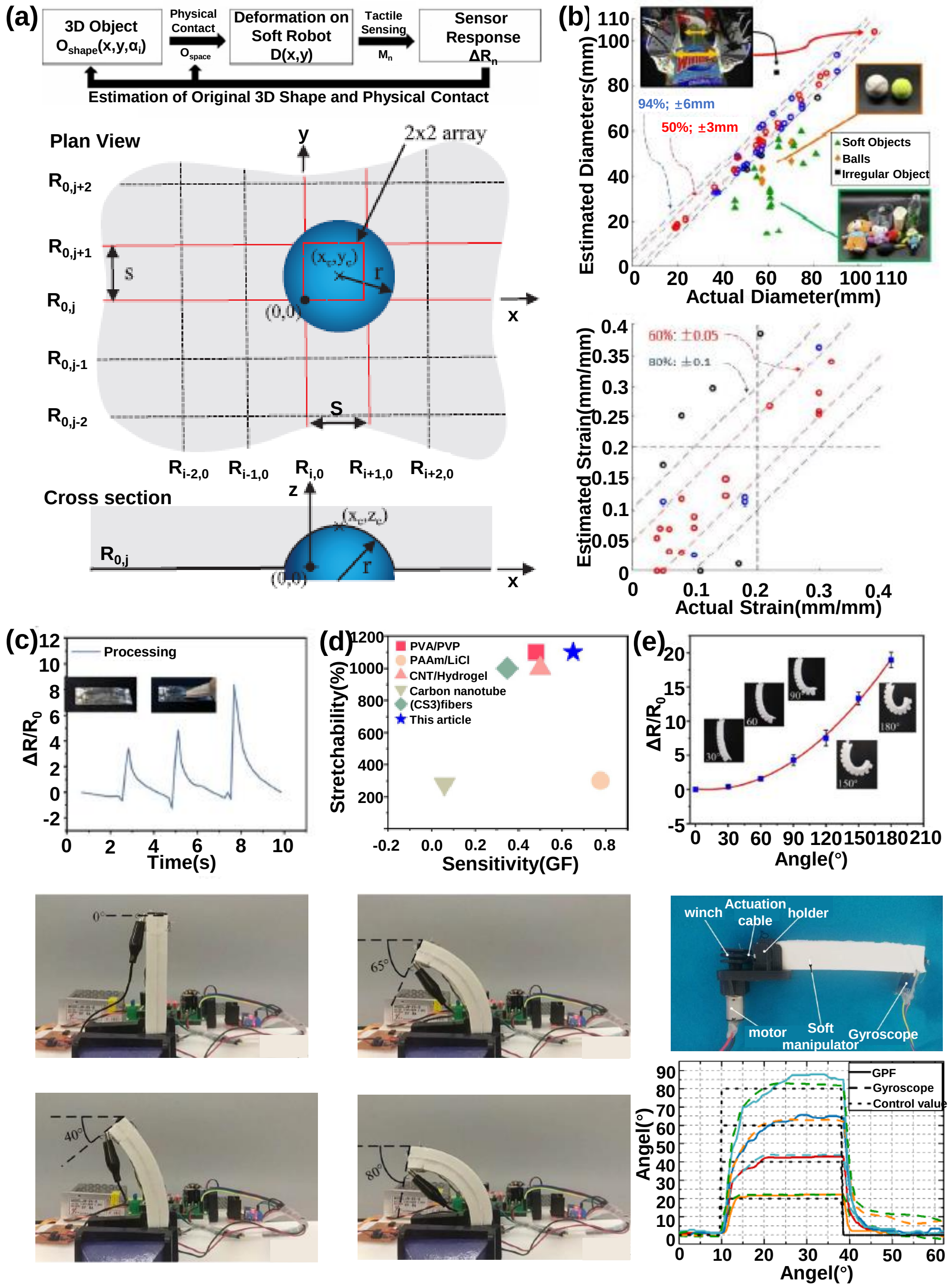


Figure 11. (a) The framework and schematic illustration of soft tactile sensing of objects.[305] Copyright 2018, Mary Ann Liebert, Inc.. (b) Comparison of actual object characteristics and sensor estimated characteristics.[306] Copyright 2020, IEEE. (c) The signals of hydrogel sensor responses to external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

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

In summary, compared with the design of the soft robot structure, the selection and breakthrough of materials for the soft robots plays an important role in the field of sensors. The soft robots used for sensor function can collect the signal, combined with machine learning can realize the learning and prediction of the 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 is a special kind of robots that can carry sensors and tools to move outside or inside. There is some related research on soft robots applied to pipeline, such as wheeled robots,[310,311] legged robots,[312] spiral robots,[313,314] and peristaltic robots,[315] etc. However, the design of previous soft robots has some problems, such as small locomotion speed, long actuation period, low load capability, etc. To improve these limitations, Zhang et al. fabricated a novel parallel-pipe-crawling pneumatic soft robot which is consisted of three extensible pneumatic soft actuator and two flexible feet (in **Figure 12a**). They optimized the performance of the designed soft robotics through the process of the structural design, finite element simulation, kinematics modeling, trajectory planning, prototype fabrication, and prototype experiments. Finally, soft robot's crawling experiments in different scenarios show that the maximum load can withstand is 2.456 kg, the crawling speed is higher than 15 mm/s, and the minimum turning radius is 38.2 mm (in **Figure 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 snake,[317] earthworm.[318,319] These bionic soft robots are commonly more flexible, however, the movement of the bionic snake soft robot in the vertical direction had been limited. Some soft robots with bionic earthworm have solved this problem. Schumacher et al. used multi-casting-based fabrication method to create a multi-material multi-actuator soft robot inspired by earthworm that can be used in a varying-slope (horizonal, vertical, oblique) transparent pipe.[73] Zhang et al. designed the soft robot inspired by earthworm can achieve sharp turnings and with large diameter change in pipelines.[318] In addition, Zhang et al. fabricated a soft robot inspired by worm that can be operated in various complicated tubular environments such as different pipeline diameters, dry, hard surfaces, water, oil, and gas environment. The robot can 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 can be used for real-time image inspection, operation, and robot tracking.[320] Xiao et al. prepared a bionic electrically driven soft robot named “Janus” which is composed of uniaxial oriented liquid crystal networks (LCNs) strip, a laminated Kapton layer, and thin resistive wires embedded in between (in **Figure 12c**). The Janus is easy to operate, can be reprogrammed, and can be reversibly transformed in shape when the electric power on and off state. The Janus can crawl in the pipeline and can be reprogrammed to adapt to different pipeline diameters. As shown in **Figure 12d**, when the diameters of the pipeline changes from 9.3 mm to 3.8 mm, the Janus can pass smoothly with speed changed from 0.75 cm min^{-1} to 0.34 cm min^{-1}. Since the Janus is composed of a single piece of material and has two parts undergoing opposite deformations simultaneously under a uniform stimulation, this allows the Janus to walk like two human legs and move three different loads at different speeds (in **Figure 12e**). This research not only opens new horizons in the development of soft robots made of liquid crystal polymer, but also provides design ideas for soft robots used for pipeline crawling and transportation engineering.[321]

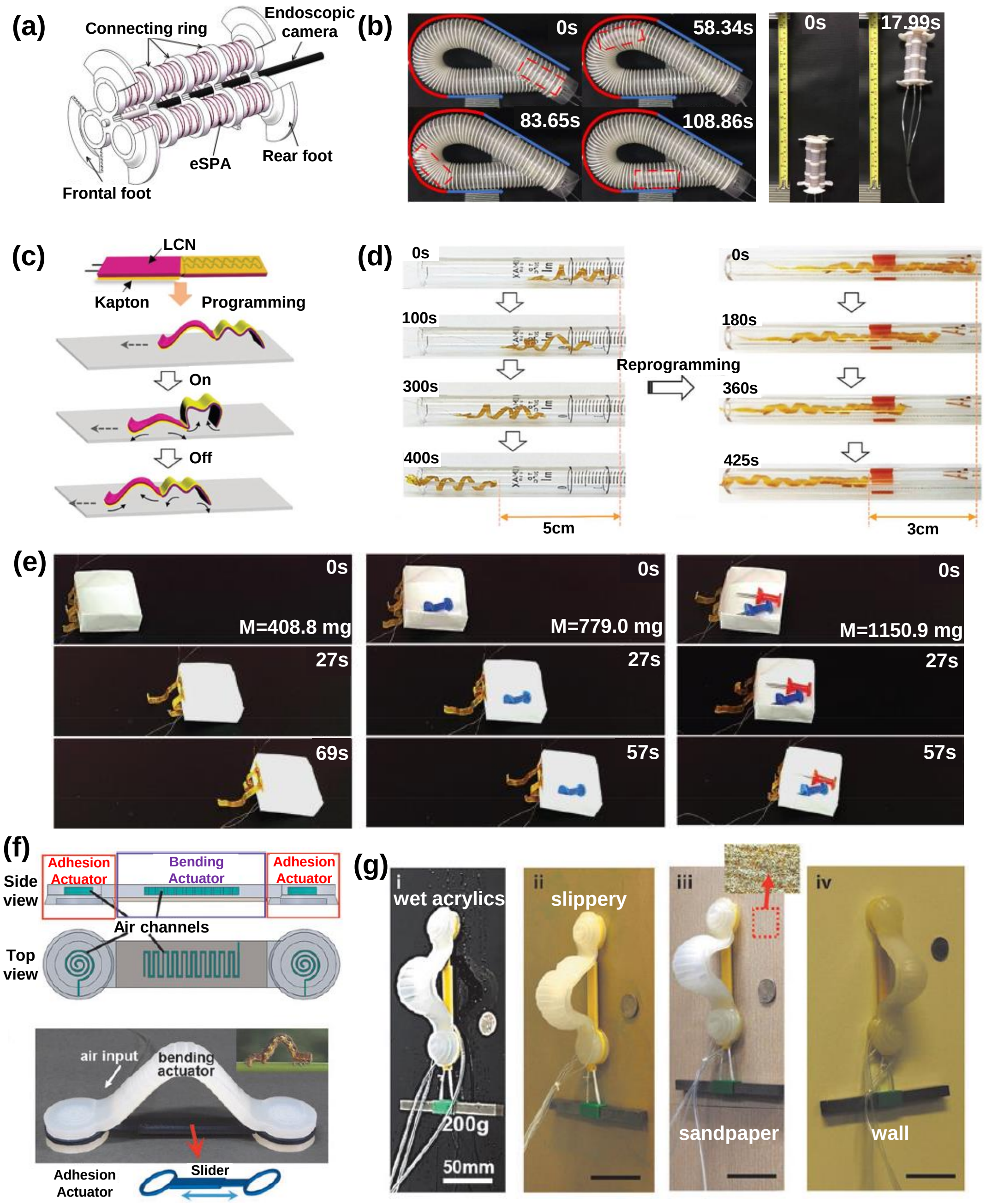


Figure 12. (a) Design structure diagram of pipe crawling soft robot. (b) Photograph of soft robot crawling in the pipeline and crawling on textured surface.[316] Copyright 2019, IEEE. (c) Schematic diagram of Janus crawling principle. (d) Crawling pictures in different diameters helical pipelines through 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..

In terms of cargo transportation, Tang et al. fabricated an amphibious climbing soft robot (ACSR) by combining the proposed switchable adhesion actuator which is inspired by inch worm. 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 the cavity (in **Figure 12f**). ACSR can adapt to various surfaces such as dry, wet, slippery, smooth on ground and under water. The vertical climbing speed of ACSR can reach to 286 mm/ min (1.6 body length/ min) and the weight of ACSR can withstand over 200 g (over 5 times of itself) (in **Figure 12g**). The ACSR with switchable adhesion property has potential application prospects in object transportation.[322] Overall, this section mainly introduced the application of soft robots in pipeline engineering and transportation engineering. The soft robots can crawl in different pipeline diameters and various surfaces environments. And the soft robot has a certain transportation capacity and can transport goods up to several times its own weight.

In this chapter, we mainly introduce the applications of soft robots including artificial intelligence, medical, sensors, and engineering. The development of these soft robots has broad application potential. However, these soft robots have limitations and needs to rely on the response of 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 recent advances in soft robotics with a specific focus on fabrication technologies, driving strategies, and applications of soft robots. The commonly used technologies in soft robot fabrication were divided into three types based on the detailed processing procedures, viz., 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 wildly used and emerging fabrication technologies in the above three types were briefly introduced. The characteristics, advantages and limits of the fabrication technologies were discussed, and 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 were reviewed, and the advantages and characteristics of different driving strategies were discussed and compared. In addition, a wide range of applications of soft robots in artificial intelligence, medical, sensor, and engineering fields were briefly introduced, and we also provided an overview of emerging soft robots/materials with good performance and application potential in these areas.

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

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 desired functions. However, the performance of biomimetic soft robots is far 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 strategy could be greatly improved by using simulation and artificial intelligence technologies. The development of fabrication technologies and updated understanding of biological knowledge could also contribute to 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 and robot intelligence, etc. Additionally, the application area of soft robots will be rapidly extended in environmental and biological fields. Soft robots have innate advantages in bio- and environmental compatibility as compared to traditional robots, and they are expected to play a key role in many areas including minimal invasive or non-invasive surgery/testing, smart drug delivery system, 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, or 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 provides a comprehensive overview of fabrication, driving strategy, and applications of soft robots and discusses the perspective of soft robotics, providing useful information for the development of new generation of soft robots.

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Reference

[1] T. Brogårdh, *Annu. Rev. Control*, **2007**, *31*, 69.

[2] I. Nourbakhsh, R. Powers, 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, G. M. Whitesides, *PNAS*, **2011**, *108*, 20400.

[4] D. Floreano, R. J. Wood, *Nature*, **2015**, *521*, 460.

[5] M. Balasingam, *Int. J. Clin. Pract.*, **2017**, *71*, e12989.

[6] Q. Wu, Y. Liu, 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, H. Geyer, *Front. Robot. AI*, **2018**, *5*, 129.

[8] A. V. Le, V. Prabakaran, V. Sivanantham, R. E. Mohan, *Sensors*, **2018**, *18*, 2585.

[9] J. B. Song, K. S. Byun, *J. Mech. Sci. Technol.*, **2009**, *23*, 2747.

[10] M. Hussein, *Adv. Robot.*, **2015**, *29*, 1575.

[11] G. Zheng, Y. Zhou, M. Ju, *ISA Trans.*, **2020**, *100*, 38.

[12] E. A. Alandoli, T. S. Lee, *Robotica*, **2020**, *38*, 2239.

[13] M. R. Cutkosky, S. Kim, *Phil. Trans. R. Soc. A*, **2009**, *367*, 1799.

[14] G. Alici, *MRS Advances*, **2018**, *3*, 1557.

[15] E. W. Hawkes, L. H. Blumenschein, J. D. Greer, A. M. Okamura, *Sci. Robot.*, **2017**, *2*, eaan3028.

[16] D. Rus, M. T. Tolley, *Nature*, **2015**, *521*, 467.

[17] D. Trivedi, C. D. Rahn, W. M. Kier, 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, G. M. Whitesides, *Soft Robot.*, **2014**, *1*, 213.

[19] K. Chubb, D. Berry, T. Burke, *Bioinspir. Biomim.*, **2019**, *14*, 063001.

[20] Trimmer, J. Barry, *Curr. Biol.*, **2013**, *23*, R639.

[21] H. Kim, J. Choi, K. K. Kim, P. Won, S. Hong, S. H. Ko, *Nat. Commun.*, **2021**, *12*, 4658.

[22] A. A. Calderón, J. C. Ugalde, J. C. Zagal, N. O. Pérez-Arancibia, *ROBIO*, Design, fabrication and control of a multi-material-multi-actuator soft robot inspired by burrowing worms, 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, L. Xue, *Mater. Today*, **2020**, *35*, 42.

[24] T. Umedachi, V. Vikas, B. A. Trimmer, *Bioinspir. Biomim.*, **2016**, *11*, 025001.

[25] A. D. Marchese, C. D. Onal, D. Rus, *Soft Robot.*, **2014**, *1*, 75.

[26] S. Wöhl, S. Schuster, *J. Exp. Biol.*, **2007**, *210*, 311.

[27] E. D. Tytell, G. V. Lauder, *J. Exp. Biol.*, **2002**, *205*, 2591.

[28] C. D. Onal, D. Rus, *Bioinspir. Biomim.*, **2013**, *8*, 026003.

[29] M. Cianchetti, M. Calisti, L. Margheri, M. Kuba, C. Laschi, *Bioinspir. Biomim.*, **2015**, *10*, 035003.

[30] B. Mazzolai, L. Margheri, M. Cianchetti, P. Dario, C. Laschi, *Bioinspir. Biomim.*, **2012,** *7*, 025005.

[31] K. Y. Su, J. Z. Gul, K. H. Choi, *Soft Robot.*, **2017,** *4*, 224.

[32] S. Wakimoto, K. Ogura, K. Suzumori, Y. Nishioka, *Adv. Robotics*, **2009**, *25*, 1311.

[33] M. Sugisaka, H. Zhao, *Artif. Life Robotics*, **2007**, *11*, 223.

[34] A. D. Marchese, K. Komorowski, C. D. Onal, D. Rus, *ICRA*, Design and control of a soft and continuously deformable 2D robotic manipulation system, 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, G. M. Whitesides, *Angew. Chem. Int. Ed.*, **2013**, *52*, 2892.

[36] C. Cheng, J. Cheng, W. Huang, *IEEE Access*, **2019**, *7*, 75073.

[37] A. Firouzeh, M. Salerno, J. Paik, *IROS*, Soft pneumatic actuator with adjustable stiffness layers for Multi-Dof Actuation, Hamburg, Germany, Sept., **2015**.

[38] K. Liu, J. Wu, G. H. Paulino, H. J. Qi, *Sci. Rep.*, **2017**, *7*, 3511.

[39] A. Albu-Schaffer, O. Eiberger, M. Grebenstein, S. Haddadin, C. Ott, T. Wimbock, S. Wolf, G. Hirzinger, *IEEE Robot. Autom. Mag.*, **2008**, *15*, 20.

[40] R. J. Wood, S. Avadhanula, R. Sahai, E. Steltz, 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, G. Hirzinger, *IEEE Robot. Autom. Mag.,* **2008**, *15*, 20.

[42] M. Jiang, Z. Zhou, N. Gravish, *Soft Robot.*, **2020**, *7*, 770.

[43] Z. Wang, K. Li, Q. He, S. Cai, *Adv. Mater.*, **2019**, *31*, 1806849.

[44] A. Stilli, H. A. Wurdemann, K. Althoefer, *Sci. Robot.*, **2017**, *4*, 16.

[45] H. Sareen, U. Umapathi, P. Shin, Y. Kakehi, J. Ou, H. Ishii, P. Maes, *CHI*, Printflatables: printing human-scale, functional and dynamic inflatable objects, Denver, USA, May, **2017.**

[46] A. Firouzeh, Y. Sun, H. Lee, J. Paik, *IROS*, Sensor and actuator integrated low-profile robotic origami, Tokyo, Japan, Nov., **2013**.

[47] C. D. Onal, R. J. Wood, D. Rus, *IEEE ASME Trans. Mechatron.*, **2012**, *18*, 430.

[48] Y. Yang, K. Vella, D. P. Holmes, *Sci. Robot.*, **2021**, *6*, 6426.

[49] G. Gu, J. Zhu, L. Zhu, X. Zhu, *Bioinspir. Biomim.*, **2017**, *12*, 011003.

[50] M. B. Trimmer, P. R. H. Ewoldt, M. Kovac, H. Lipson, N. Lu, M. Shahinpoor, C. Majidi, *Soft Robot.*, **2014**, *1*, 63.

[51] J. Zhang, E. Diller, *Soft Robot.*, **2018**, *5*, 761.

[52] A. Raatz, S. Blankemeyer, G. Runge, C. Bruns, G. Borchert, *Soft Robot.*, **2015**, 173.

[53] M. Calisti, G. Picardi, C. Laschi, *J. R. Soc. Interface*, **2017**, *14,* 20170101.

[54] M. Bächer, E. Knoop, 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, S. H. Ko, *Mater. Today*, **2020**, *41*, 243.

[56] N. Elango, A. Faudzi, *Int. J. Adv. Manuf. Technol.*, **2015**, *80,* 1027.

[57] Y. Lee, W. Song, J. Y. Sun, *Mater. Today Phys*., **2020**, *15*, 100258.

[58] H. Son, C. Yoon, *Actuators*, **2020**, *9*, 115.

[59] N. Gariya, P. Kumar, *Mater. Today: Proceedings*, **2021**, *46*, 11177.

[60] K.J. Cho, J.S. Koh, S. Kim, W.S. Chu, Y. Hong, S.H. Ahn, *Int. J. Precis. Eng. Manuf.*, **2009**, *10*, 171.

[61] Y. Yang, Y. Li, Y. Chen, *Bio-Des Manuf.*, **2018**, *1*, 14.

[62] F. Schmitt, O. Piccin, L. Barbé, B. Bayle, *Front. Robot. AI*, **2018**, *5*, 84.

[63] A. Zolfagharian, A. Kaynak, A. Kouzani, *Mater. Des.*, **2020**, *188*, 108411.

[64] S. Zaidi, M. Maselli, C. Laschi, M. Cianchetti, *Curr. Robot. Rep.*, **2021**, *2*, 355.

[65] M. A. Mousa, M. Soliman, M. A. Saleh, A. G. Radwan, *IEEE Access*, **2020**, *8*, 184524.

[66] A. Menciassi, S. Gorini, G. Pernorio, L. Weiting, F. Valvo, P. Dario, *ROBIO*, Design, fabrication and performances of a biomimetic robotic earthworm, Shenyang, China, Aug., **2004**.

[67] Z. Shen, J. Na, Z. Wang, *IEEE Robot. Autom. Lett.*, **2017**, *2*, 2217.

[68] A. D. Mazzeo, D. E. Hardt, *J. Micro. Nanomanuf.*, **2013**, *1*, 021001.

[69] W. D. Brouwer, E. Van Herpt, M. Labordus, *Compos. Part A Appl. Sci. Manuf.*, **2003**, *34*, 551.

[70] C. Wang, K. Sim, J. Chen, H. Kim, Z. Rao, Y. Li, W. Chen, J. Song, R. Verduzco, C. Yu, *Adv. Mater.*, **2018**, *30*, 1870087.

[71] H. Lipson, *Soft Robot.*, **2014**, *1*, 21.

[72] R. K. Katzschmann, A. D. Marchese, D. Rus, *Soft Robot.*, **2015**, *2*, 155.

[73] C. M. Schumacher, M. Loepfe, R. Fuhrer, R. N. Grass, W. J. Stark, *RSC Adv.*, **2014**, *4*, 16039.

[74] M. A. Bell, K. P. Becker, R. J. Wood, *Adv. Mater. Technol.*, **2021**, 7, 2100605.

[75] J. Tapia, E. Knoop, M. Mutný, M. A. Otaduy, M. Bächer, *Soft Robot.*, **2020**, *7*, 332.

[76] G. Maloisel, E. Knoop, C. Schumacher, M. Bächer, *IEEE Trans. Robot.*, **2021**, *37*, 996.

[77] P. Polygerinos, S. Lyne, Z. Wang, L. F. Nicolini, B. Mosadegh, G. M. Whitesides, C. J. Walsh, *IROS*, Towards a Soft Pneumatic Glove for Hand Rehabilitation, Tokyo, Japan, Nov., **2013**.

[78] H. Zhao, Y. Li, A. Elsamadisi, R. Shepherd, *Extreme Mech. Lett.,* **2015**, *3*, 89.

[79] S. Kriegman, A. M. Nasab, D. Shah, H. Steele, G. Branin, M. Levin, J. Bongard, R. Kramer-Bottiglio, *RoboSoft*, Scalable sim-to-real transfer of soft robot designs, New Haven, USA, Jul., **2020**.

[80] J. Germann, B. Schubert, D. Floreano, *IROS*, Stretchable Electroadhesion for Soft Robots, Chicago, USA, Sept., **2014**.

[81] C. D. Onal, D. Rus, *BIOROB*, A Modular Approach to Soft Robots, Rome, Italy, Jun., **2012**.

[82] R. V. Martinez, J. L. Branch, C. R. Fish, L. Jin, R. F. Shepherd, R. M. Nunes, Z. Suo, G. M. Whitesides, *Adv. Mater.,* **2013**, *25*, 205.

[83] Q. Wang, Z. Wu, J. Huang, Z. Du, Y. Yue, D. Chen, D. Li, B. Su, *Compos. B. Eng.,* **2021**, *223*, 109116.

[84] H. Niu, R. Feng, Y. Xie, B. Jiang, Y. Sheng, Y. Yu, H. Baoyin, X. Zeng, *Soft Robot.,* **2021**, *8*, 507.

[85] J. Zhang, A. Jackson, N. Mentzer, R. Kramer, *Front. Robot. AI*, **2017**, *4*, 46.

[86] D. Mijatovic, J. C. Eijkel, A. Van den Berg, *Lab Chip*, **2005**, *5*, 492.

[87] R. P. Chang, C. Chang, 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, J. Lee, *Adv. Healthc. Mater.,* **2021**, *10*, 2001397.

[89] V. M. Donnelly, A. Kornblit, *J. Vac. Sci. Technol. A*, **2013**, *31*, 050825.

[90] X. Sun, L. Zhuang, W. Zhang, S. Y. Chou, *J. Vac. Sci. Technol. B*, **1998**, *16*, 3922.

[91] N. Farrow, L. McIntire, N. Correll, *ICRA*, Functionalized textiles for interactive soft robotics, Singapore, Singapore, May, **2017**.

[92] Y. Jiang, Y. Wang, H. Wu, Y. Wang, R. Zhang, H. Olin, Y. Yang, *Nano-micro Lett.*, **2019**, *11*, 99.

[93] G. B. Blanchet, Y. L. Loo, J. A. Rogers, F. Gao, C. R. Fincher, *Appl. Phys. Lett.,* **2003**, *82*, 463.

[94] B. S. Shin, J. G. Kim, W. S. Chang, K. H. Whang, *Int. J. Precis. Eng. Manuf.,* **2006**, *7*, 56.

[95] H. Deng, K. Sattari, Y. Xie, P. Liao, Z. Yan, J. Lin, *Nat. Commun.,* **2020**, *11*, 1.

[96] Y. Xia, G. M. Whitesides, *Angew. Chem. Int. Ed.,* **1998**, *37*, 550.

[97] Y. X., G. M. Whitesides, *Encyclopedia of Nanotechnology*, **2003**, *37*, 153.

[98] M. Tyagi, J. Pan, E. W. H. Jager, *Microsyst. Nanoeng.,* **2019**, *5*, 44.

[99] A. Vergara, Y.S Lau, R.F Mendoza-Garcia, J.C. Zagal, *PLoS ONE*, **2017**, *12*, e0169179.

[100] F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen, 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, 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, G. M. Whitesides, *Adv. Funct. Mater.,* **2014**, *24*, 2163.

[103] W. Oropallo, L. A. Piegl, *Eng Comput*, **2016**, *32*, 135.

[104] J. Y. Lee, J. An, C. K. Chua, *Appl. Mater. Today*, **2017**, *7*, 120.

[105] H. N. Chia, B. M. Wu, *J. Med. Biol. Eng.,* **2015**, *9*, 1.

[106] N. Shahrubudin, T. C. Lee, R. Ramlan, *Procedia Manuf.,* **2019**, *35*, 1286.

[107] T. Umedachi, V. Vikas, B. A. Trimmer, *IROS*, Highly deformable 3-D printed soft robot generating inching and crawling locomotions with variable friction legs, Tokyo, Japan, Nov., **2013**.

[108] O. D. Yirmibesoglu, J. Morrow, S. Walker, W. Gosrich, Y. Menguc, *RoboSoft*, Direct 3D printing of silicone elastomer soft robots and their performance comparison with molded counterparts, Livorno, Italy, Apr., **2018**.

[109] J. Wang, A. Goyanes, S. Gaisford, A. W. Basit, *Int. J. Pharm.,* **2016**, *503*, 207.

[110] Z. K. Shao, Y. L. Jiang, *J. Mech. Electr. Eng.*, **2015**, *32*, 180.

[111] V. Chan, J. H. Jeong, P. Bajaj, M. Collens, T. Saif, H. Kong, R. Bashir, *Lab Chip*, **2012**, *12*, 88.

[112] B. N. Peele, T. J. Wallin, H. Zhao, R. F. Shepherd, *Bioinspir. Biomim.*, **2015**, *10*, 055003.

[113] M. N. I. Shiblee, K. Ahmed, M. Kawakami, 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, R. Shepherd, *J. Mater. Chem. B*, **2017**, *5*, 6249.

[115] E. B. Joyee, Y. Pan, *Procedia Manuf.*, **2019**, *34*, 566.

[116] E. B. Joyee, A. Szmelter, D. Eddington, 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, I. Smurov, *Appl. Surf. Sci.*, **2007**, *254*, 989.

[120] H. Wu, O. Wang, Y. Tian, M. Wang, B. Su, C. Yan, K. Zhou, Y. Shi, *ACS Appl. Mater. Interfaces*, **2021**, *13*, 12679.

[121] Y. S. Krieger, S. Schiele, S. Detzel, C. Dietz, T. C. Lueth, *IEEE ICRA*, Shape memory structures-automated design of monolithic soft robot structures with pre-defined end poses, Montreal, Canada, May, **2019**.

[122] A. Rost, S. Schdle, *ICMLA*, The SLS-generated Soft Robotic Hand - An Integrated Approach using Additive Manufacturing and Reinforcement Learning, Miami, USA, Dec., **2013**.

[123] D. B. Roppenecker, A. Pfaff, J. A. Coy, T. C. Lueth, *IROS*, Multi Arm Snake-Like Robot Kinematics, Tokyo, JAPAN, Nov, **2013**.

[124] S. Wei, L. Zhang, C. Li, S. Tao, B. Ding, S. Xia, H. Zhu, *J. Mater. Chem. C*, **2019**, *7*, 6786.

[125] J. G. Cham, S. A. Bailey, J. E. Clark, R. J. Full, M. R. Cutkosky, *Int. J. Robot. Res.*, **2002**, *21*, 869.

[126] J. G. Cham, S. A. Bailey, J. E. Clark, R. J. Full, M. R. Cutkosky, *ISER*, Fast and Robust: Hexapedal Robots via Shape Deposition Manufacturing, Waikiki, USA, Dec, **2000**.

[127] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, M. R. Cutkosky, *IEEE ICRA*, Whole body adhesion: Hierarchical, directional and distributed control of adhesive forces for a climbing robot, Rome, Italy, Apr., **2007**.

[128] J. Gafford, Y. Ding, A. Harris, T. McKenna, P. Polygerinos, D. Holland, C. Walsh, A. Moser, *J. Mech. Robot.*, **2015**, *7*, SI021006.

[129] A. M. Dollar, R. D. Howe, *Adv. Robot.*, **2005**, *19*, 523.

[130] K. S. Boparai, R. Singh, H. Singh, *Rapid Prototyp. J.*, **2016**, *22*, 281.

[131] A. Georgopoulou, T. Sebastian, F. Clemens, *Flex. Print. Electron.*, **2020**, *5*, 035002.

[132] A. Dijkshoorn, M. Schouten, S. Stramigioli, G. Krijnen, *Sensors*, **2021**, *21*, 3710.

[133] R. Mutlu, E. Sariyildiz, T. Nozaki, G. Alici, *IECON*, Design of A Multi-stage

Stiffness Enhancing Unit for a Soft Robotic Finger and its Robust Motion Control, Washington, DC, The United States, Oct., **2018**.

[134] H. K. Yap, H. Y. Ng, C. H. Yeow, *Soft Robot.*, **2016**, *3*, 144.

[135] J. E. M. Teoh, R. C. Mysa, T. V. Truong, P. V. Y. Alvarado, *MTS/IEEE Oceans 2020: Singapore-U.S. Gulf Coast*, Propulsive performance of an undulating fin soft robot, Online, Oct., **2020**.

[136] M. Jiang, Z. Zhou, N. Gravish, *Soft Robot.*, **2020**, *7*, 770.

[137] J. Carrell, G. Gruss, E. Gomez, *Rapid Prototyp. J.*, **2020**, *26*, 855.

[138] E. Roels, S. Terryn, J. Brancart, R. Verhelle, G. Van Assche, B. Vanderborght, *Soft Robot.*, **2020**, *7*, 711.

[139] H. M. Anver, R. Mutlu, G. Alici, *AIM*, 3D Printing of a Thin-Wall Soft and Monolithic Gripper Using Fused Filament Fabrication, Munich, Germany, Jul., **2017**.

[140] G. Stano, L. Arleo, G. Percoco, *Micromachines*, **2020**, *11*, 485.

[141] S. Singh, G. Singh, C. Prakash, 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, H.L. Ren, *IEEE Sens. J.*, **2018**, *18*, 9840.

[144] L. Y. Zhou, Q. Gao, J. F. Zhan, C. Q. Xie, J. Z. Fu, Y. He, *ACS Appl. Mater. Interfaces*, **2018**, *10*, 23208.

[145] S. Schlatter, G. Grasso, S. Rosset, H. Shea, *Adv. Intell. Syst.*, **2020**, *2*, 2000136.

[146] R. MacCurdy, R. Katzschmann, Y. Kim, D. Rus, *IEEE ICRA*, Printable Hydraulics: A Method for Fabricating Robots by 3D Co-Printing Solids and Liquids, Royal Inst Technol, Ctr Autonomous Syst, Stockholm, Sweden, May, **2016**.

[147] J. A. Lewis, 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, P. Fischer, *IEEE ICRA*, Auxetic Metamaterial Simplifies Soft Robot Design, Royal Inst Technol, Ctr Autonomous Syst, 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, R. F. Shepherd, *Extreme Mech. Lett.*, **2015**,

5, 47.

[151] M. A. Skylarscott, J. Mueller, C. W. Visser, J. A. Lewis, *Nature*, **2019**, *575*, 330.

[152] J. Choi, O. C. Kwon, W. Jo, H. J. Lee, 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, L. G. Zhang, *Tissue Eng. Part C Methods*, **2016**, *22*, 952.

[155] N. Ashammakhi, 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, 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, S. H. Kang, *ACS Appl. Mater. Interfaces*, **2019**, *11*, 8492.

[158] Q. Ge, A. H. Sakhaei, H. Lee, C. K. Dunn, N. X. Fang, M. L. Dunn, *Sci. Rep.*, **2016**, *6*, 32355.

[159] S. Janbaz, R. Hedayati, A. Zadpoor, *Mater. Horizons*, **2016**, *3*, 536.

[160] B. Jin, H. Song, R. Jiang, J. Song, Q. Zhao, T. Xie, *Sci. Adv.*, **2018**, *4*, eaao3865.

[161] J. A.-C. Liu, J. H. Gillen, S. R. Mishra, B. A. Evans, 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, L. G. Zhang, *Adv. Sci.*, **2020**, *7*, 2070034.

[163] M. Sitti, H. Ceylan, W. Hu, J. Giltinan, M. Turan, S. Yim, 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, M. Boehm, *Sci. Adv.*, **2020**, *6*, eabb5067.

[165] W. Huang, Z. Ding, C. Wang, J. Wei, Y. Zhao, H. Purnawali, *Mater. Today*, **2010**, *13*, 54.

[166] L. Sun, W. M. Huang, Z. Ding, Y. Zhao, C. C. Wang, H. Purnawali, C. Tang, *Mater. Des.*, **2012**, *33*, 577.

[167] G. Stano, 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, Z. Xie,

Adv. Mater. Technol., **2021**, *6*, 2001095.

[169] C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador, P. Dario, *Adv. Robot.*, **2012**, *26*, 709.

[170] M. Wehner, R. L. Truby, D. J. Fitzgerald, B. Mosadegh, G. M. Whitesides, J. A. Lewis, 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, M. M. Hussain, *Adv. Intell. Syst.*, **2020**, *2*, 2000128.

[172] A. D. Marchese, R. K. Katzschmann, D. Rus, *Soft Robot.*, **2015**, *2*, 7.

[173] X. Tang, K. Li, Y. Liu, D. Zhou, J. Zhao, *Smart Mater. Struct.*, **2019**, *28*, 035019.

[174] M. Calisti, M. Giorelli, G. Levy, B. Mazzolai, B. Hochner, C. Laschi, P. Dario, *Bioinspir. Biomim.*, **2011**, *6*, 036002.

[175] Y.-Y. Xiao, Z.-C. Jiang, Y. Zhao, *Adv. Intell. Syst.*, **2020**, *2*, 2000148.

[176] U. Gupta, L. Qin, Y. Wang, H. Godaba, J. Zhu, *Smart Mater. Struct.*, **2019**, *28*, 103002.

[177] J. G. Kim, J. E. Park, S. Won, J. Jeon, 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, Q. Ge, *Adv. Mater. Technol.*, **2019**, *4*, 1900427.

[179] S. G. Nurzaman, F. Iida, L. Margheri, C. Laschi, *Soft Robot.*, **2014**, *1*, 154.

[180] C. Majidi, *Soft Robot.*, **2014**, *1*, 5.

[181] L. Paez, G. Agarwal, J. Paik, *Soft Robot.*, **2016**, *3*, 109.

[182] R. F. Shepherd, A. A. Stokes, R. M. Nunes, G. M. Whitesides, *Adv Mater.*, **2013**, *25*, 6709.

[183] J. Yi, X. Chen, C. Song, Z. Wang, *Soft Robot.*, **2018**, *5*, 81.

[184] R. Deimel, O. Brock, *Int. J. Robot. Res.*, **2016**, *35*, 161.

[185] W. Hu, R. Mutlu, W. Li, G. Alici, *Robotics*, **2018**, *7*, 24.

[186] P. Moseley, J. M. Florez, H. A. Sonar, G. Agarwal, W. Curtin, J. Paik, *Adv. Eng. Mater.*, **2016**, *18*, 978.

[187] F. Chen, S. Dirven, W. Xu, 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, C. J. Thrasher, *ACS Appl. Mater. Inter.*, **2021**, *13*, 28870.

[189] J. C. Yeo, H. K. Yap, W. Xi, Z. Wang, C. H. Yeow, C. T. Lim, *Adv. Mater. Technol.*, **2016**, *1*, 1600018.

[190] F.-Y. Xu, F.-Y. Jiang, Q.-S. Jiang, Y.-X. Lu, *IEEE Access*, **2020**, *8*, 26356.

[191] C. D. Onal, X. Chen, G. M. Whitesides, 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, K. Bertoldi, *PNAS*, **2015**, *112*, 10863.

[193] H. Feng, Y. Sun, P. A. Todd, H. P. Lee, *Soft Robot.*, **2020**, *7*, 233.

[194] J. Bishop-Moser, G. Krishnan, C. Kim, S. Kota, *IROS*, Design of soft robotic actuators using fluid-filled fiber-reinforced elastomeric enclosures in parallel combinations, Vilamoura, Portugal, Oct., **2012**.

[195] K. C. Galloway, P. Polygerinos, C. J. Walsh, R. J. Wood, *Robot. Auton. Syst.*, **2014**, *73*, 135.

[196] A. D. Marchese, R. Tedrake, 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, A. Richter, *Front. Robot. AI*, **2020**, *7*, 510757.

[199] F. Berlinger, M. Duduta, H. Gloria, D. Clarke, R. Nagpal, R. Wood, *ICRA*, A Modular Dielectric Elastomer Actuator to Drive Miniature Autonomous Underwater Vehicles, Brisbane, Australia, May, **2018**.

[200] E.-F. M. Henke, S. Schlatter, 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, H.R. Choi, *IEEE ICRA*, Printable monolithic hexapod robot driven by soft actuator, Seattle, USA, May, **2015**.

[202] H. Godaba, J. Li, Y. Wang, J. Zhu, *IEEE Robot. Autom. Lett.*, **2016**, *1*, 624.

[203] E. Hajiesmaili, D. R. Clarke, *J. Phys. D*, **2021**, *129*, 151102.

[204] I. Must, E. Sinibaldi, B. Mazzolai, *Nat. Commun.*, **2019**, *10*, 1.

[205] J. Cao, L. Qin, J. Liu, Q. Ren, C. C. Foo, H. Wang, H. P. Lee, 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, A. Kakugo, *Nat. Commun.*, **2018**, *9*, 1.

[207] S. Hogreve, M. Prigge, K. O. Köbisch, K. Tracht, *Procedia CIRP*, **2020**, *91*, 439.

[208] M. C. Carrozza, G. Cappiello, E. Cavallaro, S. Micera, F. Vecchi, P. Dario, *Proceedings World Automation Congress*, **2004**, *15*, 111.

[209] V. K. Venkiteswaran, D. K. Tan, S. Misra, *Extreme Mech. Lett.*, **2020**, *41*, 101023.

[210] D.-S. Choi, T.-H. Kim, S.-H. Lee, C. Pang, J. W. Bae, S.-Y. Kim, *ACS Appl. Mater. Interfaces*, **2020**, *12*, 44147.

[211] A. M. Nasab, A. Sabzehzar, M. Tatari, C. Majidi, W. Shan, *Soft Robot.*, **2017**, *4*, 411.

[212] Q. He, Z. Wang, Y. Wang, A. Minori, M. T. Tolley, S. Cai, *Sci. Adv.*, **2019**, *5*, eaax5746.

[213] J. Zhou, S. Chen, Z. Wang, *IEEE Robot. Autom. Lett.*, **2017**, *2*, 2287.

[214] C. J. Thrasher, J. J. Schwartz, A. J. Boydston, *ACS Appl. Mater. Inter.*, **2017**, *9*, 39708.

[215] D. K. Patel, A. H. Sakhaei, M. Layani, B. Zhang, Q. Ge, S. Magdassi, *Adv. Mater.*, **2017**, *29*, 1606000.

[216] P. Iacomi, G. Maurin, *ACS Appl. Mater. Inter.*, **2021**, *13*, 50602.

[217] S. Schara, R. Blau, D. C. Church, J. K. Pokorski, D. J. Lipomi, *Adv. Funct. Mater.*, **2021**, *31*, 2008375.

[218] C. Cui, Q. Fu, L. Meng, S. Hao, R. Dai, J. Yang, *ACS Appl. Bio. Mater.*, **2020**, *4*, 85.

[219] Ube. T, Ikeda. T, *Angew. Chem. Int. Edit.*, 2014, 53, 39.

[220] J. Wang, J. Wang, Z. Chen, S. Fang, Y. Zhu, R. H. Baughman, L. Jiang, *Chem. Mater.*, **2017**, *29*, 9793.

[221] K. Mo, M. He, X. Cao, 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, D. H. Gracias, *ACS Appl. Mater. Inter.*, **2015**, *7*, 3398.

[223] F. Ongaro, S. Scheggi, C. Yoon, F. V. den Brink, S. H. Oh, D. H. Gracias, S. Misra, *J. Microbio. Robot.*, **2017**, *12*, 45.

[224] K. Kobayashi, C. Yoon, S. H. Oh, J. V. Pagaduan, D. H. Gracias, *ACS Appl. Mater. Inter.*, **2018**, *11*, 151.

[225] X. Fan, J. Y. Chung, Y. X. Lim, Z. Li, X. J. Loh, *ACS Appl. Mater. Inter.*, **2016**, *8*, 33351.

[226] Q. Fu, H. Zhang, Z. Wang, M. Chiao, *J. Mater. Chem. B*, **2017**, *5*, 4025.

[227] J. Duan, X. Liang, K. Zhu, J. Guo, L. Zhang, *Soft Matter*, **2017**, *13*, 345.

[228] X. Li, X. Cai, Y. Gao, M. J. Serpe, *J. Mater. Chem. B*, **2017**, *5*, 2804.

[229] Y. Cheng, K. Ren, D. Yang, J. Wei, *Sens. Actuators B Chem.*, **2018**, *255*, 3117.

[230] K. B. Justus, T. Hellebrekers, D. D. Lewis, A. Wood, C. Ingham, C. Majidi, P. R. LeDuc, 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, L.-Y. Chu, *ACS Appl. Mater. Inter.*, **2017**, *9*, 15758.

[232] L. Chen, C. Liu, K. Liu, C. Meng, C. Hu, J. Wang, S. Fan, *ACS nano*, **2011**, *5*, 1588.

[233] Z. S. Davidson, H. Shahsavan, A. Aghakhani, Y. B. Guo, L. Hines, Y. Xia, S. Yang, M. Sitti, *Sci. Adv.*, 2019, 5, 11.

[234] J. W. Zhou, H.-Y. Chan, T. K. To, K. W. Lai, W. J. Li, *IEEE ASME Trans. Mechatron*, **2004**, *9*, 334.

[235] E. Diller, M. Sitti, *Adv. Funct. Mater.*, **2014**, *24*, 4397.

[236] Z. Ji, C. Yan, B. Yu, X. Wang, F. Zhou, *Adv. Mater. Inter.*, **2017**, *4*, 1700629.

[237] J. Zhang, O. Onaizah, K. Middleton, L. You, E. Diller, *IEEE Robot. Autom. Lett.*, **2017**, *2*, 835.

[238] H. Yuk, S. Lin, C. Ma, M. Takaffoli, N. X. Fang, 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, 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, A. Javey, *Nat. Commun.*, 2014, 5, 2983.

[241] B. Zuo, M. Wang, B. P. Lin, 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, K. Akif, *KnE Engineering*, **2017**, *2*, 15.

[243] D. Hua, X. Zhang, Z. Ji, C. Yan, B. Yu, Y. Li, X. Wang, F. Zhou, *J. Mater. Chem. C*, **2018**, *6*, 2123.

[244] Y. Y. Yang, Y. T. Liu, Y. J. Shen, *Adv. Funct. Mater.*, 2020, 30, 14.

[245] P. Zhou, L. Chen, L. Yao, M. Weng, W. Zhang, *Nanoscale*, **2018**, *10*, 8422.

[246] J. M. Jani, M. Leary, A. Subic, M. A. Gibson, *Mater. Des.*, **2014**, *56*, 1078.

[247] M. C. Biswas, S. Chakraborty, A. Bhattacharjee, Z. Mohammed, *Adv. Funct. Mater.*, **2021**, *31*, 2100257.

[248] Y. Xia, Y. He, F. Zhang, Y. Liu, J. Leng, *Adv. Mater.*, **2021**, *33*, 2000713.

[249] M. Behl, K. Kratz, J. Zotzmann, U. Nöchel, 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, R. Zhao, *Adv. Mater.*, **2020**, *32*, 1906657.

[251] Y. Chen, X. Zhao, Y. Li, Z.-Y. Jin, Y. Yang, M.-B. Yang, B. Yin, *J. Mater. Chem. C*, **2021**, *9*, 5515.

[252] M. Liu, S. Zhu, Y. Huang, Z. Lin, W. Liu, L. Yang, D. Ge, *Compos. B. Eng.*, **2021**, *214*, 108748.

[253] X. L. Pang, L. Qin, B. Xin, Q. Liu, Y. L. Yu, *Adv. Funct. Mater.*, 2020, 30, 32.

[254] J.-H. Lee, Y. S. Chung, H. Rodrigue, *Sci. Rep.*, **2019**, *9*, 1.

[255] H. Rodrigue, W. Wang, D.-R. Kim, S.-H. Ahn, *Compos. Struct.*, **2017**, *176*, 398.

[256] F. Simone, G. Rizzello, S. Seelecke, *Smart Mater. Struct.*, **2017**, *26*, 095007.

[257] W. Wang, S.-H. Ahn, *Soft Robot.*, **2017**, *4*, 379.

[258] Y. She, J. Chen, H. Shi, H.-J. Su, *Soft Robot.*, **2016**, *3*, 71.

[259] K. Nakajima, H. Hauser, T. Li, 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, M. T. Tolley, *Sci. Robot.*, **2020**, *5*, eaaz9239.

[261] T. G. Thuruthel, B. Shih, C. Laschi, M. T. Tolley, *Sci. Robot.*, **2019**, *4*, eaav1488.

[262] P. Preechayasomboon, E. Rombokas, *Actuators*, **2021**, *10*, 30.

[263] R. L. Truby, C. Della Santina, D. Rus, *IEEE Robot. Autom. Lett.*, **2020**, *5*, 3299.

[264] L. Weerakoon, Z. Ye, R. S. Bama, E. Smela, M. Yu, N. Chopra, *ICRA*, Adaptive Tracking Control of Soft Robots Using Integrated Sensing Skins and Recurrent Neural Networks, Xi'an, China, May, **2021**.

[265] T. Jin, Z. Sun, L. Li, Q. Zhang, M. Zhu, Z. Zhang, G. Yuan, T. Chen, Y. Tian, X. Hou, *Nat. Commun.*, **2020**, *11*, 1.

[266] K. Chin, T. Hellebrekers, C. Majidi, *Adv. Intell. Syst.*, **2020**, *2*, 1900171.

[267] M. Sitti, *Nat. Rev. Mater.*, **2018**, *3*, 74.

[268] A. De Greef, P. Lambert, A. Delchambre, *Precis. Eng.*, **2009**, *33*, 311.

[269] D. B. Comber, J. E. Slightam, V. R. Gervasi, J. S. Neimat, E. J. Barth, *IEEE Trans. Robot.*, **2016**, *32*, 138.

[270] K. Suzumori, A. Koga, F. Kondo, 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, 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, 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, D. H. Gracias, *ACS Appl. Mater. Inter.*, **2015**, *7*, 3398.

[274] K. E. Gordon, G. S. Sawicki, D. P. Ferris, *J. Biomech.*, **2006**, *39*, 1832.

[275] B. G. Do Nascimento, C. B. S. Vimieiro, D. A. P. Nagem, M. Pinotti, *Artif. Organs.*, **2008**, *32*, 317.

[276] S. Wang, Z. Sun, Y. Zhao, L. Zuo, *Sens. Actuator A Phys.*, **2021**, *331*, 113006.

[277] H. Banerjee, H. Ren, *Soft Robot.*, **2017**, *4*, 191.

[278] B. Xu, X. Han, Y. Hu, Y. Luo, C. H. Chen, Z. Chen, P. Shi, *Small*, **2019**, *15*, 1900006.

[279] Z. Ren, R. Zhang, R. H. Soon, Z. Liu, W. Hu, P. R. Onck, M. Sitti, *Sci. Adv.*, **2021**, *7*, eabh2022.

[280] H. Abidi, G. Gerboni, M. Brancadoro, J. Fras, A. Diodato, M. Cianchetti, H. Wurdemann, K. Althoefer, A. Menciassi, *Int. J. Med. Robotics Comput. Assist. Surg.*, **2018**, *14*, e1875.

[281] E. B. Joyee, Y. Pan, *J. Manuf. Process*, **2020**, *56*, 1178.

[282] O. P. Ogunmolu, X. Gu, S. Jiang, N. R. Gans, *Med. Phys.*, **2016**, *42*, 3266.

[283] S. S. Yun, S. Yi, R. Brand, J. V. Zitzewitz, S. Micera, *IROS*, Soft robot for gait rehabilitation of spinalized rodents,Tokyo, Japan, Nov., **2014**.

[284] L. Lindenroth, S. Bano, A. Stilli, J. G. Manjaly, D. Stoyanov, *IEEE Robot. Autom. Lett.*, **2021**, *6*, 871.

[285] M. Cianchetti, C. Laschi, A. Menciassi, 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, R. F. Shepherd, *Adv. Eng. Mater.*, **2017**, *19*, 1700016.

[287] M. Runciman, A. Darzi, G. P. Mylonas, *Soft Robot.*, **2019**, *6*, 423.

[288] S. Terryn, J. Brancart, D. Lefeber, G. Van Assche, B. Vanderborght, *Sci. Robot.*, **2017**, *2,* eaan4268.

[289] S. Y. Hann, H. Cui, M. Nowicki, L. G. Zhang, *Addit. Manuf.*, **2020**, *36*, 101567.

[290] H. Wang, R. Zhang, W. Chen, X. Wang, R. Pfeifer, *Surg. Endosc.*, **2017**, *31*, 3152.

[291] T. Deng, H. Wang, W. Chen, X. Wang, R. Pfeifer, *ROBIO*, Development of a new cable-driven soft robot for cardiac ablation, Shenzhen, China, Dec, **2013**.

[292] J. Tang, C. Yao, Z. Gu, S. Jung, D. Luo, D. Yang, *Angew. Chem. Int. Ed.*, **2020**, *132*, 2511.

[293] W. Hu, G. Z. Lum, M. Mastrangeli, 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, J. Walsh Conor, *Sci. Trans. Med.*, **2017**, *9*, eaaf3925.

[295] H. Wang, M. Totaro, L. Beccai, *Adv. Sci.*, **2018**, *5*, 1800541.

[296] U. Culha, U. Wani, S. G. Nurzaman, F. Clemens, F. Iida, *Sensors*, **2014**, *14*, 12748.

[297] C. Mattmann, F. Clemens, G. Tröster, *Sensors*, **2008**, *8*, 3719.

[298] M. Amjadi, K. U. Kyung, I. Park, M. Sitti, *Adv. Funct. Mater.*, **2016**, *26*, 1678.

[299] Y.-L. Park, B.-R. Chen, R. J. Wood, *IEEE Sens. J.*, **2012**, *12*, 2711.

[300] J.-B. Chossat, Y.-L. Park, R. J. Wood, 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, Z. L. Wang, *Adv. Mater.*, **2011**, *23*, 5440.

[302] Y. R. Jeong, H. Park, S. W. Jin, S. Y. Hong, S. S. Lee, J. S. Ha, *Adv. Funct. Mater.*, **2015**, *25*, 4228.

[303] M. Amjadi, A. Pichitpajongkit, S. Lee, S. Ryu, I. Park, *ACS Nano*, **2014**, *8*, 5154.

[304] C. Mattmann, O. Amft, H. Harms, G. Troster, F. Clemens, *Sensors*, **2008**, *8*, 3719.

[305] J. Hughes, F. Iida, *Soft Robot.*, **2018**, *5*, 512.

[306] Z. Yang, S. Ge, F. Wan, Y. Liu, C. Song, *RoboSoft*, Scalable Tactile Sensing for an Omni-adaptive Soft Robot Finger, New Haven, The United States, Jul., **2020**.

[307] T. Gao, D. Li, G. Jin, H. Liang, R. Yang, *Nanomicro Lett.*, **2018**, *13*, 1460.

[308] X. Tang, K. Li, Y. Liu, J. Zhao, *IEEE Sens. J.*, **2018**, *18*, 6123.

[309] Q. He, Q. Zhang, *Optoelectron Lett.*, **2021**, *17*, 400.

[310] A. Kakogawa, S. Ma, *Adv. Robotics*, **2012**, *26*, 253.

[311] T. Oya, T. OkadaA, *Adv. Robotics*, **2005**, *19*, 635.

[312] K. Isaki, A. Niitsuma, M. Konyo, F. Takemura, S. Tadokoro, *IROS*, Development of an Active Flexible Cable by Ciliary Vibration Drive for Scope Camera, Beijing, China, Oct, **2006**.

[313] S. M. Liu, W. J. Shang, *Machinery.*, **2009**, *36*, 76.

[314] Y. H. Chen, Q. Y. Liu, T. Ren, *Robotica*, **2015**, *33*, 920.

[315] J. W. Qiao, J. Z. Shang, X. Chen, Z. R. Luo, X. P. Zhang, *J. Cent. South Univ. Technol.*, **2010**, *17*, 1043.

[316] Z. Zhang, X. Wang, S. Wang, D. Meng, 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, Z. Li, *IROS*, A biomimetic soft robot for inspecting pipeline with significant diameter variation, Madrid, Spain, Oct., **2018**.

[319] A. A. Calderón, J. C. Ugalde, J. C. Zagal, N. O. Pérez-Arancibia, *ROBIO*, Design, fabrication and control of a multi-material-multi-actuator soft robot inspired by burrowing worms, Macau, China, Dec., **2017**.

[320] B. Zhang, Y. Fan, P. Yang, T. Cao, H. Liao, *Soft Robot.*, **2019**, *6*, 399.

[321] Y. Y. Xiao, Z. C. Jiang, X. Tong, Y. Zhao, *Adv. Mater.*, **2019**, *31*, 1903452.

[322] Y. Tang, Q. Zhang, G. Lin, J. Yin, *Soft Robot.*, **2018**, *5*, 592.