Modular Soft Robotics: Modular Units, Connection Mechanisms, and Applications

Chao Zhang, Pingan Zhu, Yangqiao Lin, Zhongdong Jiao, and Jun Zou*

A state-of-the-art review of the modular soft robots (MSRs) is presented, with an outlook on the challenges and future directions of intelligent MSRs. In contrast to conventional robots composed of rigid materials, soft robots made from soft materials offer remarkable advantages in achieving various adaptive locomotion, manipulating delicate objects, providing safe human–robot interaction and adapting to confined environments due to their excellent compliance and adaptability, which have the potential to be widely used in numerous applications such as medical, exploration and rescue devices, etc. Unlike fixed-morphology soft robots, modularization of soft robots is a low-cost and rapid strategy that enables them to adapt to changing tasks and environments by rearranging the connectivity of module units and attain complex functionalities such as self-assembly, self-repair, or self-replication. Although MSRs exhibit many advantages, they are still in the nascent stage with plenty of challenges. Herein, first the materials, fabrication, actuation, sensor, and control of various modular units in MSRs are introduced. Then, some main connection methods between modular units are summarized. Finally, the applications, challenges, and developing directions of intelligent MSRs are discussed.

1. Introduction

Modularity is a way of decomposing a big and complex system or product into small, simple, independent, and manageable modular units that can be easily composed, decomposed, and replaced, which can be frequently found in both nature or industrial systems. In nature, small biological modular units, such as cells, DNA, muscle fibers, amino acids, genes, etc., are always combined and arranged to create various complicated biological organisms. Similar to the biological systems, modularity strategy is also widely used in industry to facilitate the fabrication, assembly, modification, and repair of products, which not only greatly reduces the manufacturing and maintenance costs of products but also improves the adaptability and versatility of the product. For robotic products or systems, the modularity strategy of robotics can offer great advantages over the fixed-morphology robots in terms of reconfigurability, reusability, mass manufacture, and easy maintenance.

In the 1960s, integrating homogeneous components to build systems was proposed by Von Neumann in his “Theory of self-reproducing cellular automata”, which was the initial conception of modular robots.[8] Later, the first modular robot called cellular robot (CEBOT) was designed and fabricated in 1988, which consisted of various types of modular units, including rotational joints, telescopic arms, and grasping modular units.[9] Since then, the modularity strategy was increasingly used to design and fabricate conventional rigid-bodied robots.[10–19] Nevertheless, incompressible and noncompliant features of the rigid-bodied robots lead to their poor adaptability and compliance in human–robot interaction tasks or confined working environments. For example, the rigid contact between rigid robots and humans or other objects readily causes undesired damage for humans or other objects, especially when the manipulation of fragile objects, and the surgical operation in narrow space of the human body. Therefore, how to make robots safer, more compliant, and more natural has attracted growing attention of scientists and engineers.

Recent advances in soft materials (e.g., elastomers,[20–23] hydrogels,[24–26] electroactive polymers,[27–31] etc.) and advanced manufacturing technologies (e.g., 3D printing,[32,33] etc.) promote the rapid development of soft robotics.[34] The bodies of soft robots made from soft materials have infinite degrees of freedom, which could bend, twist, elongate, and contract continuously and tremendously. Inherent softness makes them capable of grasping fragile objects smoothly, emulating the motions and functions of biology vividly, and operating in the confined spaces well.[35,36] Thus, soft robots have the potential to be widely used in wearable and implantable medical devices,[37–39] adaptive mobile robots,[40,41,42] and multifunctional industrial graspers,[43–46] etc. Moreover, the modularization strategy was introduced into soft robotics, offering a facile and rapid fabricating and repairing method of multifunctional soft robots. In 2012, Onal and Rus first presented a modular approach to fabricate soft robotic systems, in which the arrangements of soft modular units could achieve arbitrarily complex motions and various functionalities.[47] After that, more and more scientists and engineers have done and...
published their work on the topic of MSRs.\cite{47,48,49} Nevertheless, a review of the MSRs is still absent, whereas several reviews\cite{34,47,50,51,52,53} that focus on the materials, fabrication, and applications of soft robots already exist.

This work is intended to provide a state-of-the-art review of MSRs for those who are interested in performing researches on this topic. Some main advantages of MSRs are elaborated in Section 2. Sections 3 discusses the classification of MSRs. The materials, fabrication, actuation, sensor, and control of the modular units are introduced in Section 4, whereas the connection mechanisms between these modular units are summarized in Section 5. Section 6 focuses on the applications of MSRs. At the end of this review, the persistent challenges and future direction of intelligent MSRs are discussed.

2. Advantages of Modular Soft Robots

MSRs have three main advantages: 1) Low cost: Homogeneity of soft modular units is propitious to mass manufacturing and maintenance of soft robots, thereby significantly reducing the manufacturing and maintenance costs. 2) Good adaptability: Compared with the fixed-morphology soft robots, MSRs can actively or passively change their configurations to cope with the changeable environments and diverse tasks. 3) High robustness: Only the damaged or contaminated soft modular units in the MSRs should be replaced by good ones, instead of scrapping the whole soft robots.

3. Classification of Modular Soft Robots

In this section, the MSRs are categorized as three types based on their functionality and automaticity: 1) Assembled soft robots,\cite{48,49,50} 2) Reconfigurable soft robots,\cite{47,68,87} and 3) Self-reconfigurable soft robots.\cite{58,59}

3.1. Assembled Soft Robots

In the assembled soft robots, the arrangement and connection of module units are fixed, so the design and fabrication of module units are only for a single function or scene, not for the reconfiguration of multifunctional robots. Modularity is mainly convenient for the assembly, storage, and transportation of soft robots, as well as the rapid replacement of the failed or damaged modular units. The assembled soft robots often appear in the form of manipulators or graspers. A soft robotic manipulator could be installed as an independent soft machine or a part of existing robotic systems, which is composed of bending, rotating, and grabbing module units, as shown in Figure 1a.\cite{48}

A paper ball was grasped by a modular soft manipulator that is made of five honeycomb structure module units, as shown in Figure 1b.\cite{49} A grasper showed in Figure 1c had three modular fingers, which were designed for easy assembly and replacement.\cite{50} Moreover, some assembled soft robots are designed as mobile robots. A soft robot made of three soft spherical modular units can move through the coordinated actuation of these modular units, as shown in Figure 1d.\cite{51} Several soft modular units were assembled to form a biomimetic jellyfish robot, which could achieve 3D swimming motion, as shown in Figure 1e.\cite{52} In addition, the assembled soft robots can be used as medical devices. Some homogeneous modular units were arranged spirally to form an implantable robot, which could provide interdependent axial and radial operations, as shown in Figure 1f.\cite{53} Figure 1g shows a modular soft wearable robot made of several pneumatic muscle units and hyperelastic strain sensors, which could generate the bending deformation to assist body motions.\cite{54}

3.2. Reconfigurable Soft Robots

Different from monofunctional assembled soft robots, the reconfigurable soft robots have multiple arrangements, and thus different functionalities can be achieved by different arrangements of modular units. The modular units of the reconfigurable soft robots are not only designed for the assembly of single
soft robot or the quick replacement of damaged modular units but also for the realization of versatility. For example, some fluid-driven module units can be connected in different arrangements to form various soft robots with different functionalities (shown in Figure 2a), thereby accomplishing increasingly complicated tasks that are difficult for traditional fixed-morphology robotic systems to deal with. Three types of pneumatically actuated modular units can be rapidly assembled by different arrangements to form a gripper robot or a crawler robot (shown in Figure 2b). It can be seen from Figure 2c that a series of soft robots can be constructed by four configurations of homogenous module units, including the worm, cross, quadruped, and hexapod. Some vacuum-powered actuation modular units have been used to fabricate different soft robots, including gripper, bottle opener, rotatable crawling robot, and pipe-climbing robot (shown in Figure 2d). It can be seen from Figure 2e that a series of soft robots can be constructed by four configurations of homogenous module units, including the worm, cross, quadruped, and hexapod. Some vacuum-powered actuation modular units have been used to fabricate different soft robots, including gripper, bottle opener, rotatable crawling robot, and pipe-climbing robot (shown in Figure 2d). Similarly, different soft robots made by different arrangements of soft deformable modular units could achieve different motions, as shown in Figure 2e. Similarly, some researchers have developed different deploying configurations of the triangular mast, which comprised of homogeneous module units.

3.3. Self-Reconfigurable Soft Robots

Self-reconfigurable soft robots can autonomously transform their morphologies to cope with changeable environments or tasks, and can also replace the damaged modular units by themselves. As shown in Figure 3, the automatic connection process of two MSRs was conducted, where two 3 × 3 array robots crawled toward and formed a new 3 × 6 array, and the new 3 × 6 array robot was still capable of moving in three degrees of freedom. In addition, a teleoperator was used to control the disassembly of soft robots, where a leg of the crawled robot was automatically unloaded via the inflation of the bladder. However, these aforementioned MSRs only realized the self-reconfiguration process simply, and self-reconfigurable soft robots are still at the infant stage. Currently, there is no strong self-reconfigurable soft robotic because some challenging issues remain to be solved, such as self-awareness, intercommunication between modular units, assembly and disassembly of modular units, etc.

4. Modular Units

Modular units are the basis and core of MSRs. In this section, the material, fabrication, actuation, sensor, and control of modular units are discussed.

4.1. Materials and Fabrication

Recent advances in soft materials provide a good basic condition for the advancement of MSRs. Compared with rigid robots, soft robots made from soft materials exhibit outstanding adaptability and compliance, enabling them to adapt to the environment by changing themselves. As shown in Figure 4, soft materials are the materials with Young's modulus in the order of 10⁴–10⁹ Pa, including biological muscle tissue, skin, etc. In general, the commonly used soft materials for MSRs can be divided into two types: 1) elastomer materials such as silicone rubber, which are mainly driven by pneumatic or hydraulic actuation to generate deformation; 2) smart materials such as dielectric elastomer, ionic polymer–metal composite...
Under the pneumatic or hydraulic actuation, the silicone rubbers can exhibit tremendous and continuous deformation without the leakage of gas or liquid. Silicone rubbers are nontoxic, tasteless, odorless, and do not adhere to human tissue, thus they are especially suitable to be used as medical materials. Meanwhile, silicone rubbers exhibit good damage resistance when they are punctured by needle or knocked by a hammer. In addition, silicone rubbers also have outstanding properties at low and high temperatures, thermal and oxidative stability, good water and chemical resistance, and excellent electrical insulation properties. Except for the silicone rubbers, shape memory alloys (SMAs), as flexible material, also play an important role in the fabrication of modular units of MSRs. SMAs have shape memory effect through thermoelastic and martensitic transformation. Due to the large actuation force and displacement, the SMAs are mainly used in modular mobile soft robots and modular soft grippers. However, the poor irreversibility of SMA hinders their widespread use in MSRs. Of course, some other polymeric materials were also used for creating modular units by researchers, but there are still few studies on this issue. Advanced fabrication technologies, especially the 3D printing, also play important roles in the development of soft modular units. So far, many innovative fabrication methods, including soft lithography, lost wax casting, 3D printing, etc., have been developed and used to fabricate soft modular units. Soft lithography is a technique used to create microdevices or 3D structures with internal channels by means of molding and embossing an elastomer on a mold. Typical soft lithography fabrication procedures of a fluidic elastomer modular unit with

![Image](image-url)
Many researchers have used soft lithography to fabricate different soft modular units. Although this method is widely used to fabricate the modular units with more fluidic channels, in the multi-step lamination process of soft lithography there are obvious bonding seams that are not firm and easily tore under the high pressure. To produce the soft modular units with arbitrarily shaped internal channels but no seams, the lost wax casting is a good choice. Lost wax casting is a process, where a core model of the complex internal channels is first fabricated using paraffin wax with low melting point; then the wax core model is put into another outer mold and the uncured polymer materials (e.g., silicone rubbers, etc.) are poured into the mold; after the curing of silicon rubber, the wax core is dissolved and the soft
4.2. Actuation

Soft robotics is a branch of robotics featured by innovative actuation methods, and the development of actuation methods will greatly promote the advancement of soft robotics. Different from the rigid actuation counterparts (e.g., impellers, bearings, electrical motors, etc.) of conventional rigid robots that are usually bulky and produce noise,[4] the actuation counterparts of soft robots are always flexible, quiet, and stretchable. To date, many actuation methods are used in soft robots, which are mainly classified based on physical signals, such as electrical,[29,30,104,106] thermal,[108–111] pressure,[22,23,112,113] light,[114–116] combustion,[117,118] etc. In terms of MSRs, the pneumatic actuation and SMA actuation are two main actuation methods widely adopted by scientists and engineers due to the widespread use of silicone rubbers and SMAs. In this part, these actuation methods are summarized, and the different desired deformation types of soft modular units (i.e., bending, extension, shrinking, twisting, etc.) are also reviewed.

Pneumatic actuation is the most commonly used method for actuating the modular units of MSRs, which offers great advantages in large output force, high controllability, good safety, and low cost. The basic principle of pneumatic actuation is that the desired deformation of modular units is achieved by inflating the elastomer actuator with gas. Different deformation behaviors, such as bending, elongation, shrinking, and twisting, etc., have been widely studied and used in the pneumatic actuation of modular units, which are discussed in the following.

4.2.1. Bending Actuation

The bending deformation is the most commonly used actuation form in the pneumatic actuation of modular units. The methods to realize bending actuation of modular units could intrinsically be divided into three types: 1) selectively pressurizing different chambers of the modular units; 2) asymmetric structure designs of the modular units; and (3) utilization of different materials in the modular units. As shown in Figure 6a, there are three chambers in a modular unit; the polydirectional bending deformation could be achieved by selectively pressurizing different chambers.[76] Different from the strategy of selectively pressurizing different chambers, the asymmetric structure designs of the modular units can achieve bending deformation under the same pneumatic pressure based on the different deformation capability of asymmetric structures in different parts of the modular units. In Figure 6b, two soft fingers with different asymmetric structures are shown, and these asymmetric structures of upper and lower sides will cause the different bending amplitude of them.[50] In addition, modular units made from different stiffness materials will also produce bending actuation under the same pneumatic pressure. As shown in Figure 6c[49] and Figure 6d,[47] in the modular units, the stiffness of the side with a filler or constraint layer is larger than that of another side without filler or constraint layer, leading to their bending deformation. These strategies have also been widely adopted in other modular units to achieve bending actuation.[50,61]

4.2.2. Elongation or Inflation Actuation

Elongation or inflation is also an important actuation form of pneumatic modular units. When the soft modular units are filled with pressurized gas, they inevitably expand their volumes and achieve the elongation or inflation deformation. As shown in Figure 6e, when the three chambers of a module unit were all filled with the equal volume of pressurized gas at the same time, it would elongate its length.[49] Figure 6f showed an inflation process of a soft cube modular unit due to which the pressurized gas was filled into it.[82] It is apparent that both elongation and inflation of modular units result from an increase in volume. However, the elongation deformation occurs when the radial deformation of modular units is constrained, whereas inflation deformation occurs without the constraints of radial deformation.

4.2.3. Shrinking Actuation

The shrinking actuation is an important actuation form of pneumatic artificial muscle units. As shown in Figure 6g, a McKibben pneumatic artificial muscle unit has been developed to generate shrinking deformation in the length direction when the gas is filled into the channel of the artificial muscle.[54] In addition, the shrinking of a modular soft cylinder can be achieved under negative pressure, whereas the restoration of shrinking can be obtained using positive pressure, as shown in Figure 6h.[88]

4.2.4. Twisting Actuation

The twisting actuation of modular units usually depends on their special structure designs. As shown in Figure 6i, the modular unit is predesigned as the helical structure.[68] When the air is filled into the channel of the modular unit, the twisting will generate along with the predesigned structure. However, this twisting performance is poor, where the twisting angle is only 3° under gas pressure of 50 kPa. In addition, the origami structure is used in the design of modular units, thereby generating twisting actuation, as shown in Figure 6j. However,
the twisting of these origami-inspired modular units are accompanied by other motions, contraction, and bending. Interestingly, the single twisting motion can be achieved by the combinations of two modular units.\cite{70,71}

SMA actuators are also widely used to actuate soft modular units, which have great advantages in easy manufacturing and programming, high ratio power/mass, low-voltage power supply, silent operation, and biocompatible.\cite{119} As shown in Figure 7a, a modular unit consists of an actuation layer made of SMAs wires and a recovery layer made of polyvinyl chloride polymer, which could realize bending and recovery motions.\cite{52} As shown in Figure 7b, other deformable modular units made of SMAs wires have also been created to reconfigure MSRs.\cite{73} These actuation modular units are widely used in crawling robots, biomimetic jellyfish, gripper, etc. Except for pneumatic actuation and SMA actuation, a special electromagnetic actuation method has also been used to actuate soft modular units, in which each flexible modular unit embedded with electromagnetic coil or permanent magnet can be extended or contracted axially through applying current in different polarity.\cite{60}

---

**Figure 6.** a) Vacuum actuated modular unit with three air chambers can bend in different directions. Reproduced with permission.\cite{49} Copyright 2017, American Association for the Advancement of Science. b) The two modular fingers with different structures could both achieve bending deformation. Reproduced with permission.\cite{109} Copyright 2016, IEEE. c) The finger that the inner sides of back walls are filled up with silicone rubber, which can generate bending deformation when air is inflated into the central part. Reproduced under the terms of the CC-BY 4.0 License.\cite{49} Copyright 2017. The Authors, published by SAGE Publications Ltd. d) The bending deformation of a modular unit with a constraint sheet. Reproduced with permission.\cite{43} Copyright 2012, IEEE. e) The cylindrical modular unit could generate stretching deformation when gas is simultaneously pressurized into three chambers. Reproduced under the terms of the CC-BY 4.0 License.\cite{49} Copyright 2017. The Authors, published by SAGE Publications Ltd. f) The relative motions between neighboring modular units could be realized through the inflation deformation of the central unit. Reproduced under the terms of the CC-BY License.\cite{82} Copyright 2017. The Authors, published by PLOS. g) The relaxed and contracted states of a pneumatic artificial muscle unit. Reproduced with permission.\cite{54} Copyright 2012, IEEE. h) The restored and shrinking deformation of a soft unit under barometric pressure and negative pressure, respectively. Reproduced with permission.\cite{88} Copyright 2018, Mary Ann Liebert, Inc. i) The twisting deformation of a modular unit. Reproduced with permission.\cite{84} Copyright 2016, IEEE. j) The origami-inspired modular units could generate hybrid deformations under vacuum supply, and these hybrid motions can be decoupled to twisting by combining two units. Reproduced with permission.\cite{70,71} Copyright 2019, John Wiley & Sons, Inc.
To date, various control methods offer choices, which facilitate high-level control of soft robots. However, when a soft system is desired, coupled control methods are necessary to be integrated with the module units. The deformer feature of modular units leads to the high demands for sensors. The sensors should not only be able to bend and stretch as the modular units deform but also can precisely measure the information during the deformation process. Thus, many conventional sensors, including encoders, strain gauges, or inertial measurement units (IMUs), are not suitable for soft modular units. To date, various flexible sensors have been explored for soft modular units. There are two main strategies to make modular units achieve information perception: one is that embedding flexible sensor (e.g., pressure sensor, optical sensor, micro-magnet, light-sensitive resistor, etc.) into modular units to achieve the desired information perception (e.g., curvature, position, etc.); another method is to make modular units themselves as sensors, such as injecting conductive liquid into the channels of modular units, and utilizing the self-perception ability of SMAs. Although several kinds of flexible sensors have been developed for soft modular units, they are still in the preliminary stage and only a small amount of simple information could be measured by existing flexible sensors. Self-perception and environmental perception are indispensable elements to build intelligent soft modular units, and thus advanced sensors with flexible, compact, reliable and multidimensional features are necessary to be developed. Many outstanding works have been reported about this topic, and some relative reviews can be referred to understand this topic better.

The control of soft robots with continuous deformation and high degree of freedom redundancy is a tremendous challenge. Existing soft robots mainly adopted low-level open-loop control without proprioceptive sensors or other information feedback. In contrast to open-loop control, the model-based control methods offer choices, which facilitate high-level control of soft robots. Some researchers have done some work to realize the precise motions of soft robots based on model-based methods. Typically, the piecewise constant curvature approach was used for modeling the motion trajectory of soft robots. Finite element methods were also used to analyze the influence of geometric parameters on the deformation of soft robots. In addition, dynamic models were proposed for better control performance of soft robots, including Ritz–Galerkin models and the discrete Cosserat models. Although there are some advances in the model-based method, this topic is in the nascent stage in the field of soft robotics. Similarly, the open-loop control method is the most widespread method for the control of soft modular units. Especially, the open-loop control method is usually used to simply control the pressurization or depressurization of pneumatically driven soft modular units. For example, the modular omnidirectional quadruped robots were controlled by open-loop control of different modular units to achieve omnidirectional motions. There are still some model-based control methods that were used to control soft modular units. A caterpillar-like modular robot with large and continuum deformation was controlled by an autonomous decentralized system based on a 2D-mathematical model. The finite element method was used to control the forward kinematics of modular units. A direct sliding-mode controller algorithm was applied in soft bidirectional bending modular units, which could offer faster response speeds. So far, the control of soft modular units is still at a low level; the high-level control methods should be explored and used in the control of modular units, thereby realizing the intelligent modular units in the future.

5. Connection Mechanisms

Compared with fixed-morphology robots, the remarkable feature of modular robots is the reversible connection of modular units, which facilitates the replaceability of modular units and morphology change of robots. Thus, connection methods will directly affect the operation efficiency of modular robots and are crucial for delivering the full potential advantages of modularization strategy. In modular rigid robots, the connection mechanisms can be broadly classified into two main categories based on the imposed force: 1) mechanical connections and 2) magnetic connections. Among these, the mechanical connections can be further divided into pin and hole, hooks, lock and key, shape matching, etc. However, when a soft system is desired, coupled...
connectors should not greatly reduce the softness of the modular units. Ideally, the connection mechanism could be incorporated in soft modular units without introducing rigid components, then showcasing a good performance, such as high reliability, high robustness, etc.; for example, the connectors should keep their interconnections active even if modular units are largely deformed under the harsh state. Based on the aforementioned objectives, several connection methods have been developed for MSRs, including mechanical, magnetic, adhesive, vacuum, etc. The major advantages and disadvantages of these connection methods are summarized in Table 1.

Mechanical connections are one of the most commonly used connection methods of existing MSRs due to their high reliability and high alignment precision, which can be classified as rigid mechanical connections and soft mechanical connections. Rigid mechanical connections are easily available connection method with high connection strength and good alignment precision. Many publications have reported the application of the rigid mechanical connections in MSRs. For example, using interchangeable gender-specific connectors, a modular soft robotic wrist can be formed by connecting soft modular units in series, thereby achieving the desired working envelope.\(^\text{96}\) A rigid mechanical connection method, termed Legris push-in fitting, was used to firmly connect the tubes and tube unions, thereby constructing an easily modifiable MSR.\(^\text{74}\) In addition, a reliable snap-lock connection mechanism with gender interfaces enable the rigid connectors to connect the base of the modular gripper without using screws.\(^\text{100}\) Rigid mechanical connectors also make it possible to produce a plug-and-play modular soft units with both pneumatic and electronic connections via rigid mating interfaces.\(^\text{76,84}\) However, the introduction of rigid mechanical connection components into soft robots greatly reduces their compliance and adaptability and also increases the mechanical and structural complexities. In contrast to rigid mechanical connectors, soft mechanical connectors are made from soft materials, which can maintain the compliance of whole soft robots. A series of soft mechanical connectors, including bistable connector, screw-thread connector, and push-fitting connector, have been shown in Figure 8, where the bistable design could make the connection more flexible, the screw-thread design could achieve the strong connection between assembling units, and push-fitting design could make the connection simpler and easier.\(^\text{68}\) However, the purely soft mechanical connection could not undertake high pressure or large force, thereby leading to the leakage of fluids (gas or liquid). Thus, joint strength should be taken into consideration when designing such connections.

Magnetic connections are also largely used in the connection of soft modular units, which have the advantages in easy attachment and self-aligning connection. There are already numerous examples of magnetic connections of soft modular units. An intuitive and reliable magnetic connection method is shown in Figure 9a, in which the design of the sealing ring enables these connectors to obtain good connection strength and air leakage prevention.\(^\text{109}\) A mobile soft robot was built via the magnetic connection of homogeneous quadrilateral modular units, as shown in Figure 9b.\(^\text{73}\) Some cube modular units could be easily connected with each other when the magnets were embedded in them, as shown in Figure 9c and d.\(^\text{82}\) Nevertheless, there are also some shortcomings in the existing magnetic connection. First of all, the integrated magnets inevitably introduce rigid components into soft robots, thus increasing the rigidity of soft robots. In addition, permanent magnets usually need extra actuation for detachment. The electromagnets could easily achieve detachment, but the requirement of extra power will increase the complexity of systems.

Adhesive connections, including glued adhesion, hot-melt adhesion, electrostatic adhesion, etc., is a connection method

| Connection mechanism | Advantages | Disadvantages | Reference |
|----------------------|------------|---------------|-----------|
| Mechanical           | Rigid connector | High connection strength | Add complexity to the modular units | [50,56,74,76,84] |
|                      | Soft connector | Good alignment precision | Add rigidity to soft modular units | |
| Magnetic             | Permanent magnet | Easy attachment | Need extra actuation to disconnection | [59,73,82,88] |
|                      |              | High connection strength | Add rigidity to soft modular units | |
|                      | Electromagnet | Easy connection and disconnection | Need an extra power source | [63] |
|                      |              | High connection strength | Adding complexity to modular units | |
|                      |              | Self-aligning | Adding rigidity to soft modular units | |
| Adhesive             | Glued       | High connection strength | One-off and irreversible | [86] |
|                      |              | Low design requirements | |
| Hot-melt             | Easy connection and disconnection | Need an extra heating strategy | [135] |
|                      | Compact design | |
| Electrostatic        | Not require precise alignment | Need an extra power source | [136] |
|                      | Easy connection and disconnection | Low connection strength | |
| Vacuum               | Sucker      | Easy connection and disconnection | Depend on precise alignment | [71] |
|                      |              | High connection strength | Require an integrated pump actuation system | |
of MSRs without introducing any rigid or soft connection counterparts. Among these, the glued adhesion can guarantee a high connection strength and leakproofness while the design and fabrication of any connection structures are not needed. For instance, multiple legs made of special tubes were glued together to build a mobile modular soft robot, in which high connection strength can avoid the leakage of air in connectors. Nevertheless, one-off glued adhesion causes great difficulty in the disconnection of the modular units and even brings undesired damage to other modular units or robots in the disassembled process. In addition, a hot-melt adhesive connection method was proposed to achieve automatic connection and disconnection of soft modular units by controlling the temperature variation of the viscoelastic material. However, the extra heating strategies and devices are needed to change the temperature of such material, which adds the redundancy of the robotic systems. Some researchers introduced the electrostatic adhesion into MSRs to allow for easy connection and disconnection without precise alignment. Although many advantages are offered by electrostatic adhesion, the electroadhesive substances should be connected to a high-voltage supply to produce high electrostatic forces which hinder extensive usage of electroadhesive methods in the field of MSRs.

Vacuum connections can be used to connect soft modular units to form modular soft robots, which have the advantage in easy connection and disconnection. Using vacuum suckers, a pipe-climbing robot and a flexible wrist are created by connecting different modular units, as shown in Figure 10a,b. However, the connection of vacuum suckers has low automation, and the realization of connection usually requires extra forces. Meanwhile, the good connection depends on the precise alignment of the connected areas.

So far, the connection mechanisms of MSRs are mainly based on four types: 1) mechanical connections, 2) magnetic
connections. 3) adhesive connections, and 4) vacuum connections. According to the characteristics of different modular soft robots, these connection mechanisms were properly adopted to construct different MSRs. As mentioned earlier, the mechanical connections have the advantages of high alignment accuracy and high connection strength, thus these easily available methods are widely used in MSRs. Magnetic connections are often chosen to build the MSRs due to their characteristic of easy detachment. For the convenience of design, adhesive connections are usually used in the connection of MSR without introducing any extra counterparts. The vacuum connection is introduced into MSRs for its strong connection and controlled disconnection. In addition to the aforementioned common connection methods, some novel connection methods (such as electrostatic connection, hot-melt connection, etc.) have been explored, which provide useful enlightenment for the development of MSRs connection mechanism.

Nevertheless, these main connections have their own limitations. For instance, mechanical connections are usually difficult to be detached, especially when the self-reconfiguration is desired. Magnets would introduce extra counterparts so as to reduce the compliance and flexibility of MSRs. Permanent magnets would need an extra actuation mechanism for detachment, which would introduce the extra weight and power source into MSR. Although electromagnets could realize the automatic detachment, they would consume high amounts of power for continuous operation. In addition, the adhesion connections are always one-off or need an extra power source or other devices to achieve detachment. Vacuum connections such as the sucker also require an extra pump actuation to support the connection and detachment of modular units. For MSRs, there are still long-standing challenges to develop connection mechanisms that do not limit the softness of the MSRs, do not require precise alignment, and allow for easy detachment, etc. Furthermore, wireless connections of autonomous information exchange will also be a great challenge for MSRs.

6. Applications of Modular Soft Robots

MSRs not only have the inherent advantages of soft robots in achieving various locomotion, manipulating delicate objects, providing safer human–robot interaction, and adapting to confined environments but also have the advantages of modularity in rapid fabrication and maintenance. Thus, they are widely used in many fields. As shown in Figure 11, some main applications are summarized and the details are given in the following.

6.1. Flexible Gripper of Industrial Robots

With the development of industrial automation, various products will be fabricated by the production line. The soft robots have inherent security, which can change their shapes to cover the objects well according to the shapes and sizes of the objects, therefore they have a good advantage in the shape of irregular objects, especially fragile objects grasp. Modular soft grippers composed of assembled and replaceable fingers can further promote adaptability and reduce the cost of industrial production.68,30,61,64

6.2. Medical Devices

Compared with rigid robots, soft robots can better meet the needs of certain medical operations. Soft robots have great degrees of freedom, and their materials’ properties are similar to that of living organisms. They can move into complex internal cavities of living organisms without causing damage to organs and tissues. Soft robots can reproduce the motion of joints in the human body very well and can make close contact with the human body without any harm, so they have great advantages in the rehabilitation wearable devices, such as upper limb gloves for rehabilitation training for stroke patients or fracture patients, ankle-assisted training device.53,54 The modular soft robots can
In these situations, different application connections of MSRs include the swarm Lee et al. have introduced the modularized design for soft robotics from the inspiration of LEGO, and some toy robots (e.g., soft gripper, scorpion-inspired robot, etc.) had been seamlessly assembled with soft LEGO and conventional LEGO bricks. There are several advantages in creating toys by soft modular units. On the one hand, the introduction of soft materials makes the plaything more soft and comfortable. On the other hand, the reconfigurable characteristic of MSRs greatly promotes the entertainment through toys and helps in children’s intellectual development.

6.3. Rescue and Exploration Devices

Soft robots have good damage resistance and can operate in small spaces, so they can be well used in the environments of exploration, searching, and rescue. In these situations, the tasks or environments to be performed are difficult to be known a priori. Therefore, it is impossible to manufacture suitable soft robots in advance so as to cope with the environments and complete the tasks smoothly. Especially, in an emergency or lack of resources, the modular soft robots are very useful and meaningful. The modular soft robots can cope with different situations and save a lot of time. For example, self-sustaining and self-repair robots that can handle unforeseen and complicated circumstances are required in space missions, and MSRs offer a good solution in this regard.

6.4. Entertainment

Much potential for applications in toys, education, and entertainment exists for modular soft robotics. Lee et al. have introduced the modularized design for soft robotics from the inspiration of LEGO, and some toy robots (e.g., soft gripper, scorpion-inspired robot, etc.) had been seamlessly assembled with soft LEGO and conventional LEGO bricks. There are several advantages in creating toys by soft modular units.

On the one hand, the introduction of soft materials makes the plaything more soft and comfortable. On the other hand, the reconfigurable characteristic of MSRs greatly promotes the entertainment through toys and helps in children’s intellectual development.

7. Challenges and Future Trends

Although the research of MSRs has some progress, it is still at a low level as the existing MSRs could only achieve simple configurations and accomplish some easy tasks. There are many challenges that need to be overcome with advanced technologies or approaches in the future, to achieve high-performance MSRs that are self-contained, agile, powerful, intelligent, and versatile.

First of all, the capacity and function of modular units would directly determine the performance of MSR, and thus further development of the modular unit is imperative. Self-contained modular units should be realized by integrating actuation, sensor, control, power, etc. Among these, the actuation of modular units should be safe, controllable, powerful, flexible, and portable. Strong self-perception and environment perception of modular units should be achieved by embedding a variety of advanced sensors such as visual recognition, voice recognition, flexible touch, etc. The model-based formal control of soft modular units, as well as soft robots, is necessary. Developments in energy-harvesting techniques (e.g., mechanical, thermoelectric, photovoltaic, and electrochemical) and wireless power transmission are expected to play a key role in addressing the power of robotics. In addition, artificial intelligence will be inevitably introduced into modular units to cope with changeable environments or tasks by themselves. In addition, the inherent low stiffness of soft materials cannot allow modular units to complete tasks that require high load capacity, such as grasping heavy objects. To address this issue, the stiffness-tunable mechanisms (e.g., layer jamming, media jamming, etc.) should be integrated into the soft modular units, which enable them to be able to selectively behave like traditional rigid ones.

Secondly, the connection mechanisms of MSRs should also be improved, including physical connections and information connections. Existing connection mechanisms mainly allow for the simple assembly and passive reconfiguration of modular units. Although a few scholars have studied active self-reconfiguration technology, they are still in the preliminary stage. Ideal connection mechanisms should not only achieve the good physical connections that introduce a few extra counterparts into systems and allow for easy detachments of modular units, etc. Meanwhile, information connection should be built among modular units, which make the connections intelligent. To some extent, “intelligent” connections of MSRs include the swarm modular units, where independently acting modular units cannot achieve a goal by themselves but, in coordination with other modular units, can solve complex problems and complete a mission. This “force multiplication” requires individuals to sense their neighbors and to communicate with other individuals in their team while acting independently. This paradigm has always been seen in natural organisms, such as fish, birds, and insects. Recent rapid development in 5G wireless technologies, big data science, machine learning, and predictive analytics, and so on,
will provide strong technical support for the future development of these intelligent connections.

In addition, the construction of MSR usually starts from the design inspirations, which is the core issue in building MSR. Nature is full of modular elements, and thus inspiration from nature is an important way. For example, complex biological organisms are made up of countless cells. Biological organisms could well adapt to different environments and accomplish various tasks after a long period of evolution so as the researchers could incorporate these capabilities into their designs. Some researchers have taken inspiration from the cytoskeleton of living cells, and morphogenetic movements of the embryo. In addition, there are also some great inspirations from engineering for building MSRs, such as building bricks, origami, etc. These ideas inspired by biology and engineering provide important approaches to develop MSRs.

Acknowledgements

C.Z. and P.Z. contributed equally to this work. This work was supported by the National Natural Science Foundation of China under grant No. 51875507 and 51890885.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

connection mechanisms, modular soft robots, modular units, soft materials

Received: December 9, 2019
Revised: February 11, 2020
Published online: April 14, 2020

[1] M. A. Schilling, Acad. Manag. Rev. 2000, 25, 312.
[2] S. Murata, H. Kurokama, IEEE Robot. Autom. Mag. 2007, 14, 71.
[3] S. R. Chennareddy, A. Agrawal, A. Karuppiah, J. Robot. 2017, 2017, 1.
[4] W. Saab, P. Racioppo, P. Ben-Tzvi, Robotica 2019, 37, 378.
[5] M. Yim, W. Shen, B. Salemi, D. Rus, M. Moll, H. Lipson, K. Eric, G. S. Chirikjian, IEEE Robot. Autom. Mag. 2007, 14, 43.
[6] D. Bao, X. Wang, H. Huang, B. Liang, presented at 2nd Workshop on Advanced Research and Technology in Industry Applications (WARTIA 2016), Dalian, China, May 2016.
[7] K. Gilpin, D. Rus, IEEE Robot. Autom. Mag. 2010, 17, 38.
[8] J. Neumann, Theory of Self-Reproducing Automata, University of Illinois Press, Champaign 1966.
[9] T. Fukuda, S. Nakagawa, presented at IEEE International Conference on Robotics and Automation, Philadelphia, PA, USA, April 1988.
[10] M. Yim, D. G. Duff, K. D. Rousas, presented at IEEE International Conference on Robotics and Automation, San Francisco, April 2000.
[11] C. Unsal, P. K. Khosla, presented at 2000 IEEE International Conference on Robotics and Automation, San Francisco, April 2000.
[12] H. Kurokawa, K. Tomita, A. Kamimura, S. Kokaji, T. Hasuo, S. Murata, Int. J. Rob. Res. 2008, 27, 373.
[13] P. J. White, M. Yim, Int. J. Rob. Res. 2010, 29, 598.
[14] M. Gajamohan, M. Merz, I. Thommen, R. D’Andrea, in IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, Vilamoura 2012, pp. 3722–3727.
[15] J. Davey, N. Kwok, M. Yim, in IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, Vilamoura 2012, pp. 4464–4469.
[16] T. Han, N. Ranasinghe, L. Barrios, W. M. Shen, presented at IEEE International Conference on Robotics and Biomimetics (ROBIO), Guangzhou, China, December 2012.
[17] J. Zhao, X. Wang, H. Jin, D. Bie, Y. Zhu, Int. J. Adv. Robot. Syst. 2015, 12, 32.
[18] X. Wang, H. Jin, Y. Zou, B. Chen, D. Bie, Y. Zhang, J. Zhao, Robot. Comput. Integr. Manuf. 2016, 39, 56.
[19] D. Bie, M. A. Gutiérrez-Naranjo, J. Zhao, Y. Zhu, Commun. Comput. Inf. Sci. 2017, 791, 24.
[20] 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.
[21] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, C. J. Walsh, Robot. Auton. Syst. 2015, 73, 135.
[22] S. A. Morin, R. F. Shepherd, S. W. Kwok, A. A. Stokes, A. Nemiroski, G. M. Whitesides, Science 2012, 337, 828.
[23] R. F. Shepherd, F. Ilievski, W. Choi, S. A. Morin, A. A. Stokes, A. D. Mazzeo, X. Chen, M. Wang, G. M. Whitesides, Proc. Natl. Acad. Sci. 2011, 108, 20400.
[24] L. Ionov, Mater. Today 2014, 17, 494.
[25] J. Kim, J. A. Hanna, M. Byun, C. D. Santangelo, R. C. Hayward, Science 2012, 335, 1201.
[26] H. Banerjee, H. Ren, Soft Robot. 2017, 4, 191.
[27] J. Youn, S. M. Jeong, G. Hwang, H. Kim, K. Hyeon, J. Park, K. Kyung, Appl. Sci. 2020, 10, 640.
[28] W. H. Mohdlsa, A. Hunt, S. H. HosseinNia, Sensors 2019, 19, 3967.
[29] J. J. Hubbard, M. Fleming, V. Palmre, D. Pugal, K. J. Kim, K. K. Leang, IEEE J. Ocean. Eng. 2014, 39, 540.
[30] S. Shian, K. Bertoldi, D. R. Clarke, Adv. Mater. 2015, 27, 6814.
[31] G. Y. Gu, J. Zhu, L. M. Zhu, X. Zhu, Bioinspiration Biomimetics 2017, 12, 1.
[32] T. J. Wallin, J. Pikul, R. F. Shepherd, Nat. Rev. Mater. 2018, 3, 84.
[33] J. Z. Gul, M. Sajid, M. M. Rehman, G. U. Siddiqui, I. Shah, K. H. Kim, J. W. Lee, K. H. Choi, Sci. Technol. Adv. Mater. 2018, 19, 243.
[34] H. Lipson, Soft Robot. 2014, 1, 21.
[35] S. Kim, C. Laschi, B. Trimmer, Trends Biotechnol. 2013, 31, 287.
[36] J. Hughes, U. Culha, F. Giardina, F. Guenther, A. Rosendo, F. Iida, Front. Robot. AI 2016, 3, 1.
[37] M. Rairo, J. M. Walker, A. M. Okumura, H. Culbertson, presented at IEEE International Conference on Robotics and Automation (ICRA), Singapore, May 2017.
[38] C. T. O’Neill, N. S. Phipps, L. Cappello, S. Paganoni, C. J. Walsh, IEEE Int. Conf. Rehabil. Robot. 2017, 02129, 1672.
[39] E. T. Roche, M. A. Horvath, I. Wamala, A. Alazmani, S. E. Song, W. Whyte, Z. Machaidze, C. J. Payne, J. C. Weaver, G. Fishbein, J. Kuebler, N. V. Vasilyev, D. J. Mooney, F. A. Pigula, C. J. Walsh, Sci. Transl. Med. 2017, 9, 1.
[40] A. D. Marchese, R. K. Katzschmann, D. Rus, Soft Robot. 2015, 2, 7.
[41] D. Drotman, S. Jadhav, M. Karimi, P. Dezonia, M. T. Tolley, presented at IEEE International Conference on Robotics and Automation (ICRA), Singapore, May 2017.
[42] K. Suzumori, S. Endo, T. Kanda, N. Kato, H. Suzuki, presented at IEEE International Conference on Robotics and Automation (ICRA), Roma, Italy, April 2007.
[43] R. Deimel, O. Brock, presented at IEEE International Conference on Robotics and Automation (ICRA), Karlsruhe, Germany, May 2013.
[44] S. Lichte, E. Collins, M. L. Mendes, C. Baxter, Soft Robot. 2017, 4, 305.
[44] I. D. S. Chathuranga, Z. Wang, D. S. Chathuranga, S. Hirai, presented at IEEE International Conference on Robotics and Biomimetics (ROBIO) 2016, Qingdao, China, December 2016.

[45] Z. Chen, C. Zhao, Y. Zhang, Y. Zhu, J. Fan, J. Zhao, J. Phys. Conf. Ser. 2019, 1207, 012006.

[46] Y. Zhou, H. Jin, C. Liu, E. Dong, M. Xu, J. Yang, presented at IEEE International Conference on Robotics and Biomimetics (ROBIO) 2016, Qingdao, China, December 2016.

[47] D. S. Chathuranga, S. Hirai, presented at IEEE International Conference on Robotics and Biomimetics, Nagoya, Japan, June 2017.

[48] E. R. Perez-Guagnelli, S. Nejus, J. Yu, S. Miyashita, Y. Liu, D. D. Damian, presented at IEEE International Conference on Robotics and Automation (ICRA), Brisbane, Australia, May 2018.

[49] S. Yim, M. Sitti, presented at IEEE Int. Conf. on Robotics and Automation 2018, Bologna, Italy, June 2018.

[50] T. Ranzani, A. Menciassi, C. Caccia, E. Fumagalli, M. H. Rosen, G. Petroni, A. Menciassi, presented at 3rd Workshop on Soft Robot Assisted Surgery, Florence, Italy, September 2013.

[51] I. D. Falco, M. Cianchetti, A. Menciassi, Bioinspiration Biomimetics 2017, 12, 11.

[52] J. Y. Lee, K. J. Cho, presented at 4th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI) 2017, Jeju, Jeju, Korea, June 2017.

[53] M. P. Nemitz, P. Mihaylov, T. W. Barraclough, A. A. Stokes, Soft Robot. 2016, 3, 198.

[54] B. S. Homberg, R. K. Katzschmann, M. R. Dogar, D. Rus, presented at IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, Germany, September 2015.

[55] Y. Fei, H. Gao, Nonlinear Dyn. 2015, 82, 891.

[56] Y. Fei, H. Gao, Nonlinear Dyn. 2014, 78, 831.

[57] A. K. Mishra, E. Del Dottore, A. Sadeghi, A. Mondini, B. Mazzolai, Front. Robot. AI 2017, 4, 1.

[58] W. Pang, Y. Fei, W. He, presented at Proc. of the 2016 Int. Conf. on Machine Learning and Cybernetics, Jeju, South Korea, July 2016.

[59] A. D. Marchese, R. K. Katzschmann, D. Rus, IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, IEEE, Chicago, IL, 2014, pp. 554–560.

[60] M. Chiantetti, T. Ranzani, G. Gerboni, I. D. Falco, C. Laschi, A. Menciassi, IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, IEEE, Tokyo, 2013, pp. 3576–3581.

[61] J. Y. Lee, W. B. Kim, W. Y. Choi, K. J. Cho, IEEE Robot. Autom. Mag. 2016, 23, 30.

[62] Y. Zhang, T. Zheng, J. Fan, G. Li, Y. Zhu, J. Zhao, IEEE Access 2019, 7, 11128.

[63] Z. Jiao, C. Ji, J. Zou, H. Yang, M. Pan, Adv. Mater. Technol. 2019, 4, 1.

[64] Z. Jiao, C. Zhang, W. Wang, M. Pan, H. Yang, J. Zou, Adv. Sci. 2019, 6, 01371.

[65] W. Wang, H. Rodrigue, S. H. Ahn, Sci. Rep. 2016, 6, 1.

[66] W. Wang, N. C. Kim, H. Rodrigue, S. H. Ahn, Mater. Horiz. 2017, 4, 367.

[67] A. D. Horchler, A. Kandhari, K. A. Daltorio, K. C. Moses, J. C. Ryan, K. A. Stultz, E. N. Kanu, K. B. Andersen, J. A. Kershaw, R. J. Bachmann, H. J. Chiel, R. D. Quinn, Soft Robot. 2015, 2, 135.

[68] J. Germann, A. Maesani, R. Pericet-Camara, D. Floreano, Soft Robot. 2014, 1, 239.

[69] M. A. Robertson, J. Paik, presented at IEEE International Conference on Intelligent Robots and System Vancouver, BC, Canada, September 2017.

[70] S. A. Morin, Y. Shevchenko, J. Lessing, S. W. Kwok, R. F. Shepherd, A. A. Stokes, C. M. Whitesides, Adv. Mater. 2014, 26, 5991.

[71] H. Jin, E. Dong, G. Alici, S. Mao, X. Min, C. Liu, K. H. Low, J. Yang, Bioinspiration Biomimetics 2016, 11, 056012.

[72] S. Hamill, B. Plee, P. Ferenz, M. Westerfield, R. F. Shepherd, H. Kress-Gazit, Int. Symp. Exp. Robot. Springer, Cham 2016.

[73] H. Jin, E. Dong, M. Xu, C. Liu, G. Alici, Y. Jie, Smart Mater. Struct. 2016, 25, 085026.

[74] S. Yim, M. Sitti, presented at IEEE Int. Conf. on Robotics and Automation (ICRA), Karlsruhe, Germany, May 2013.

[75] A. Vergara, Y. S. Lau, R. F. Mendoza-Garcia, J. C. Zagal, PLoS One 2017, 12, 1.

[76] A. Nemiroisky, Y. Y. Shevchenko, A. A. Stokes, B. Unal, A. Ainla, S. Albert, C. Compton, E. MacDonald, Y. Schwab, C. Zellofer, G. M. Whitesides, Soft Robot. 2017, 4, 183.

[77] M. A. Robertson, J. Paik, Sci. Robot. 2017, 2, 1.

[78] D. Zappetti, S. Mintchev, J. Shintake, D. Floreano, presented at Biomimetics and Biohybrid Systems: 6th International Conference Living Machines, Stanford, CA, USA, July 2017.

[79] J. Y. Lee, J. Eom, W. Y. Choi, K. J. Cho, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, Madrid 2018, pp. 7513–7520.

[80] S. A. Morin, S. W. Kwok, J. Lessing, J. Ting, R. F. Shepherd, A. A. Stokes, C. M. Whitesides, Adv. Funct. Mater. 2014, 24, 5541.

[81] J. Zou, Y. Lin, C. Ji, H. Yang, Soft Robot. 2018, 5, 164.

[82] S. W. Kwok, S. A. Morin, B. Mosadegh, J. H. So, R. F. Shepherd, R. V. Martinez, B. Smith, F. C. Simeone, A. A. Stokes, G. M. Whitesides, Adv. Funct. Mater. 2014, 24, 2170.

[83] F. Schmitt, O. Piccin, L. Barbé, B. Bayle, Front. Robot. AI 2018, 5, 1.

[84] M. Cianchetti, M. Manti, V. Cavicchioli, C. Laschi, Robot. Autom. Mag. 2016, 23, 93.

[85] S. I. Rich, R. J. Wood, C. Majidi, Nat. Electron. 2018, 1, 102.

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

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

[88] L. Hines, K. Petersen, G. Z. Lum, M. Sitti, Adv. Mater. 2017, 29, 1604383.

[89] A. Miriyev, K. Stack, H. Lipson, Nat. Commun. 2017, 8, 1.

[90] C. Lee, M. Kim, Y. J. Kim, N. Hong, S. Ryu, H. J. Kim, S. Kim, Int. J. Control. Autom. Syst. 2017, 15, 3.

[91] G. Bao, H. Fang, L. Chen, Y. Fan, F. Xu, Q. Yang, L. Zhang, Soft Robot. 2018, 5, 229.

[92] 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.

[93] C. Laschi, B. Mazzolai, M. Cianchetti, Sci. Robot. 2016, 1, 1.

[94] 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.

[95] T. Li, G. Li, Y. Liang, T. Cheng, J. Dai, X. Yang, B. Liu, Z. Zeng, Z. Huang, Y. Luo, T. Xie, W. Yang, Sci. Adv. 2017, 3, 1.
[103] W. Sun, F. Liu, Z. Ma, C. Li, J. Zhou, J. Appl. Phys. 2016, 120, 084901.
[104] I. A. Anderson, T. A. Gisby, T. G. McKay, B. M. O’Brien, E. P. Calius, J. Appl. Phys. 2012, 112, 041101.
[105] J. Najem, D. J. Leo, Electroact. Polym. Actuators Devices 2012, 8340, 83401Q.
[106] Z. Chen, T. I. Um, H. Bart-Smith, Sens. Actuators A Phys. 2011, 168, 131.
[107] R. V. Martinez, A. C. Alvan, C. Keplinger, A. I. Oyetibo, G. M. Whitesides, Adv. Funct. Mater. 2014, 24, 3003.
[108] A. Menciassi, S. Corini, C. Pernorio, P. Dario, presented at IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA’04, New Orleans, LA, USA, April 2004.
[109] C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador, P. Dario, Adv. Robot. 2012, 26, 709.
[110] A. Villanueva, C. Smith, S. Priya, Bioinspiration Biomimetics 2011, 6, 036004.
[111] S. Bressers, S. Chung, A. Villanueva, C. Smith, S. Priya, Behav. Mech. Multifunct. Mater. Compos. 2010, 7644, 76440G.
[112] R. K. Katzschmann, A. D. Marchese, D. Rus, Exp. Robot. 2016, 109, 405.
[113] D. Yang, M. S. Verna, J. H. So, B. Mosadegh, C. Keplinger, B. Lee, F. Khashai, E. Lossner, Z. Suo, G. M. Whitesides, Adv. Mater. Technol. 2016, 1, 31.
[114] M. Rogdž, H. Zeng, C. Xuan, D. S. Wiersma, P. Wasyliczyk, Adv. Opt. Mater. 2016, 4, 1689.
[115] S. Palagi, A. G. Mark, S. Y. Reigh, K. Melde, T. Qiu, H. Zeng, C. Parmeggiani, D. Martella, A. Sanchez-Castillo, N. Kapernaum, F. Giesselmann, D. S. Wiersma, E. Lauga, P. Fischer, Nat. Mater. 2016, 15, 647.
[116] H. Zeng, O. M. Wani, P. Wasyliczyk, A. Priimagi, Macromol. Rapid Commun. 2018, 39, 1.
[117] 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. Chemie Int. Ed. 2013, 52, 2892.
[118] N. W. Bartlett, M. T. Tolley, J. T. B. Overvelde, J. C. Weaver, B. Mosadegh, K. Bertoldi, G. M. Whitesides, Science 2015, 349, 161.
[119] L. Miková, S. Medvecká-Beňová, M. Kelemen, F. Trebuňa, I. Virgala, Metalurgija 2015, 54, 169.
[120] M. Luo, E. H. Skorina, W. Tao, F. Chen, S. Ozel, Y. Sun, C. D. Onal, Soft Robot. 2017, 4, 117.
[121] R. K. Kramer, C. Majidi, R. J. Wood, presented at IEEE International Conference on Robotics and Automation Shanghai, China, May 2011.
[122] A. Nag, S. C. Mukhopadhyay, J. Kosel, IEEE Sens. J. 2017, 17, 3949.
[123] Q. Li, L. N. Zhang, X. M. Tao, X. Ding, Adv. Healthcare Mater. 2017, 6, 1.
[124] H. Liu, Q. Li, S. Zhang, R. Yin, X. Liu, Y. He, K. Dai, C. Shan, J. Guo, C. Liu, C. Shen, X. Wang, N. Wang, Z. Wang, R. Wei, Z. Guo, J. Mater. Chem. C 2018, 6, 12121.
[125] T. Han, A. Nag, N. Afsarimanesh, S. C. Mukhopadhyay, S. Kundu, Y. Xu, Sensors 2019, 19, 1.
[126] Q. Sun, B. Qian, K. Uto, J. Chen, X. Liu, T. Minari, Biosens. Bioelectron. 2018, 119, 237.
[127] M. Amjadi, K. U. Kyung, I. Park, M. Sitti, Adv. Funct. Mater. 2016, 26, 1678.
[128] R. J. Webster, B. A. Jones, Int. J. Rob. Res. 2010, 29, 1661.
[129] Z. Zhang, J. Dequidt, A. Kruszewski, F. Largilliere, C. Duriez, presented at IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) Daejeon, South Korea, October 2016.
[130] A. Lismonde, V. Sonneville, O. Brüls, IFAPapersOnLine 2017, 50, 6016.
[131] S. M. H. Sadati, S. E. Naghibi, I. D. Walker, K. Althoefer, T. Nanayakkara, IEEE Robot. Autom. Lett. 2018, 3, 328.
[132] F. Renda, V. Cacucciolo, J. Dias, L. Seneviratne, presented at IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) Daejeon, South Korea, October 2016.
[133] T. Umedachi, B. A. Trimmer, presented at IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Daejeon, South Korea, October 2016.
[134] G. Runge, M. Wiese, A. Raatz, presented at IEEE International Conference on Robotics and Biomimetics (ROBIO), Macau, China, December 2017.
[135] L. Wang, F. Iida, presented at 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), Roma, Italy, June 2012.
[136] J. Germann, M. Dommer, R. Pericet-Camara, D. Floreano, Adv. Robot. 2012, 26, 785.
[137] E. W. Hawkes, L. H. Blumenschein, J. D. Greer, A. M. Okamura, Sci. Robot. 2017, 2, 1.
[138] A. Rafsanjani, Y. Zhang, B. Liu, S. M. Rubinstein, K. Bertoldi, Sci. Robot. 2018, 3, 1.
[139] R. K. Katzschmann, J. DelPreto, R. MacCurdy, D. Rus, Sci. Robot. 2018, 3, 3449.