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REVIEW ARTICLE

Biomedical soft robots: current status and perspective

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Abstract

This paper reviews the current status of soft robots in biomedical field. Soft robots are made of materials that have comparable modulus of elasticity to that of biological systems. Several advantages of soft robots over rigid robots are safe human interaction, ease of adaptation with wearable electronics and simpler gripping. We review design factors of soft robots including modeling, controls, actuation, fabrication and application, as well as their limitations and future work. For modeling, we survey kinematic, multibody and numerical finite element methods. Finite element methods are better suited for the analysis of soft robots, since they can accurately model nonlinearities in geometry and materials. However, their real-time integration with controls is challenging. We categorize the controls of soft robots as model-based and model-free. Model-free controllers do not rely on an explicit analytical or numerical model of the soft robot to perform actuation. Actuation is the ability to exert a force using actuators such as shape memory alloys, fluid gels, elastomers and piezoelectrics. Nonlinear geometry and materials of soft robots restrict using conventional rigid body controls. The fabrication techniques used for soft robots differ significantly from that of rigid robots. We survey a wide range of techniques used for fabrication of soft robots from simple molding to more advanced additive manufacturing methods such as 3D printing. We discuss the applications and limitations of biomedical soft robots covering aspects such as functionality, ease of use and cost. The paper concludes with the future discoveries in the emerging field of soft robots.

Keywords Soft robot · Soft actuator · Robotic fabrication · Modeling of soft robot · Biomimetic · Biomedical robots

1 Introduction

Robots are in use in every industry, and they render a valuable service in our daily lives. General applications of robots have been implemented into the workforce to take off manual labor aiming to increase the efficiency of the production lines [1, 2]. Healthcare, automotive, aviation, food production and agriculture are just few examples of fields that operate with heavy reliance on robots [3–7].

Present-day robots are mainly rigid, since they are composed of hard structural elements to perform different tasks [8]. Soft robotics is an emerging technology that has the potential to provide novel solutions that rigid robots are not capable of addressing with satisfaction. Soft robots do not contain rigid joints or require a fully mechanical system to complete actuation [9]. They are capable of conforming to the surface of any geometry without causing damage [10, 11].

The development of soft robots is a growing interdisciplinary field of study and experimentation involving research in chemistry, material sciences, mechanics and electronics to name a few [12, 13]. Unlike rigid-body robots that have a finite number of joints and degrees of freedom, soft robots are made of flexible materials such as silicone and operate by continuous deformation [14, 15]. Soft robotics is on the brink of affecting several industries across the globe today.

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They are heavily sought after due to their ability to be multifaceted in application, capable of handling delicate items, ability to emulate the human body and their ability to work in a variety of conditions that rigid robots cannot perform [16–18].

A distinct advantage of soft robots in medical field is the possibility of designing the components to distribute forces evenly over larger areas of contact. This feature prevents damage caused by relatively high force concentrations at discrete points of contact due to compliance matching to human body [19–21]. Therefore, soft robots are safe to interact and interface with humans as assistive devices [22, 23]. Another advantage of soft robots over rigid robots is the soft material's intrinsic ability to adapt to a wide variety of stimuli with limited use of sensors [24, 25]. Rigid robots require sophisticated sensors to safely interact with soft objects [26, 27]. Even with these sensors, they tend to cause irritation and damage to soft objects [28–31].

Soft robots experience diverse working conditions and environment, and they require different manufacturing techniques [32]. With the advancement of additive manufacturing technology, it is now possible to design, mold and fabricate soft robots with relative ease and a wide variety of materials [33, 34]. As a result, materials selected for soft robots and their manufacturing techniques show some uniqueness as will be discussed in this article.

Despite the many advantages soft robots display, they have their shortcomings as well. Soft robots are typically unable to withstand heavy loads and survive a large quantity of actuation. They also pose challenges with precise controls because of near-infinite degrees of freedom [35–38]. Another significant challenge in developing soft robotic systems is the difficulty of accurately modeling the mechanical behavior [39–41]. Traditional robots are normally modeled as rigid components connected to discrete joints with relative ease. Because soft robots are composed of flexible materials and are designed to deform continuously, it is a daunting task to model their behavior. Thus, it becomes essential to develop robust and accurate mathematical and numerical models of these robots to analyze and optimize their design [42, 43].

The flexibility of the materials themselves is another challenge with soft robots. Soft robots respond to their environment and their loads based on their intrinsic material properties and not as much on inputs from sensors. Therefore, they can deform in undesired or unpredictable ways such as sagging from their own weight. More research and experimentation are needed to address these challenges and improve the functionality of soft robots [44, 45].

In recent years, scientists focused on customizing the properties of soft materials to address these challenges. There is a considerable amount of ongoing efforts in designing methods for control and movement including pneumatic, thermal and chemical actuation methods [46–50]. While there has been much done, there are still many challenges to address for realizing the full potential of this fascinating branch of robotics. Four key elements to consider when designing a soft biomedical robot are:

1. Modeling the mechanical behavior,
2. Controls of the robot,
3. Actuation of the robot, and,
4. Fabrication of the soft body.

This paper reviews the state-of-the-art biomedical soft robots. We survey methods for modeling the mechanical behavior, techniques for controlling soft robots, actuation, and methods of fabrication. We will also discuss the applications of soft robots in the biomedical field, their limitations and the future work as outlined in the following sections.

2 Modeling of soft robots

This section presents different concepts for developing numerical and mathematical models of soft robots. Modeling and simulation techniques used for robotics systems are based on kinematics, multibody dynamics or finite element methods. Kinematic techniques focus on the path of a chain-like end-effector. Multibody dynamic techniques add the physical interactions using real mechanical properties such as contact and friction. These models provide a description of the robotic system and its physical environment. Feedback controls are used to account for modeling uncertainties. Finite element methods model the nonlinear details of the robot, the environment and their interactions. They are mainly used for analysis and design of the robot and their integration with controls is computationally a complex task for real time processing [51, 52].

2.1 Kinematic models

The mechanical model of a soft robot is very complicated due to the nonlinearities in materials, geometry and loading. There has been several studies attempting to develop biomechanical models for predicting the behavior of a soft animal and human appendages [53, 54]. The kinematic model of an octopus arm is such as an example. In this model, sending a simple propagating activation signal to contract all muscles along the arm produces an extension with kinematic properties similar to those of natural movements. Controls of only two parameters fully specified the motion of the robots. These two parameters are the amplitude of the activation signal, and the activation traveling time [55]. This approach suggests that the octopus arm could use minimal amplitudes of activation to generate the minimal muscle forces required for the production of the desired kinematics. Larger-amplitude signals would generate larger forces that increase the arm's stability against perturbations without changing the kinematic characteristics. The robustness of this phenomenon was demonstrated by examining activation signals with either a constant or a bell-shaped velocity profile. This modeling technique suggests that the octopus arm biomechanics may allow independent control of kinematics and resistance to perturbation during arm extension movements.

Napadow et al. [56] developed a model of the human tongue to determine if movement is dependent on the intrinsic longitudinal and transverse muscles. Experimental models of muscular hydrostats such as the octopus arm and tongue can help to better understand the mechanics of motion for soft robots. Biological experiments can be used as a basis for modeling actuators of which the analysis and data are vital to validate the accuracy. The kinematics of such robots can be considered using the piecewise-constant-curvature model [57].

2.2 Multibody models

There has been several methods to replicate the movement of soft bodies using multibody dynamics techniques as well. To evaluate positioning, grasping and the outcome of surgeries, a model of the hand as a multibody system was developed [58]. The hand consists of movable joints, where each joint experienced a moment produced by the contraction of muscles crossing joints. Yang et al. [59] demonstrated an experimental approach to discover the use and coactivity of tendons in the hand to determine the contribution of each tendon by applying a force transducer to a finger. Santello et al. [60] used the synergic interaction between neural inputs and movements of the hand to reveal the muscular force mechanism.

Multibody models describing the force distribution of contact surfaces such as the fingertips assume the relationship between stresses and strains, and deformations due to contact. These models can provide a close approximation of the actual behavior of a finger or other soft objects [61]. This research compared modeling techniques of the human finger by analyzing the relationship between contact loads caused by rotational friction. It was found that modeling the fingertip as a liquid-filled membrane most closely and completely match the forces and parameters experienced by an actual fingertip. This model can be improved using a proxy-based algorithm that decouples the tangential forces and rotational forces. The characterization of frictional contact of a fingertip must be modeled as a non-planar contact, due to the elastic body composure of the finger. Ciocarlie et al. [62] modeled a soft finger using a non-planar technique to consider forces that are transmitted through a deformable fingertip to compare effectiveness of the grasping ability.

2.3 Finite element models

Kinematic and multibody models provide good approximation of the robot. However, computationally intensive methods such as finite element analysis must be used to more accurately model the behavior of a biological appendage. As an example, calculating the radial and axial stretch of a soft actuator with varying fiber angle is challenging due to the heterogeneous composition of the structure. Finite element methods are the only technique for such complex problems [63].

As shown by Suzumori et al. [64], the design of a soft pneumatic actuator can be modeled using finite element analysis to properly consider the non-linearity of the elastomer material properties. Cheney et al. [65] determined that a voxel engine such as the VoxCAD soft body simulator is better suited to model the non-linear deformation of heterogeneous soft actuators. Finite element method is the basis for analyzing a voxel-based mass-spring-damper model.

Another technique to model soft robot interaction is the "Soft Cell Simulator". Here, a soft multi-cellular robot is analyzed in 2D. They used a pressure based model for the soft mechanical behavior of the single cells, and they scaled the model to multiple cells for modeling the entire robot and its interaction [66].

3 Controls of soft robots

Although controls of rigid and semi-rigid robots have reached their technology maturity, they are not well applicable to soft robots with infinite degrees of freedom [67]. Since soft robots have high dimensionality, it is extremely difficult to develop models accurately describing their dynamics. Therefore, conventional control methods have limited applications in soft robotics [68]. Figure 1 shows the operational domain of a soft robot and different levels of mapping involved in the controls [69]. Controls of soft robots can be classified into model-based and model-free methods.

3.1 Model-based control methods

Most of the techniques used in controls of soft robots are model-based, and they use piecewise-constant-curvature assumption [70]. This model assumes that the configuration space of a 3D soft robot can be parameterized by three variables [71]. This assumption maps the infinite dimensional space into 3D, and it ignores a large portion of the end-effector dynamics. This approach can easily be used for simple hydraulic and pneumatic controls.

Hydraulic control offers a direct linear control of the actuator kinematics. To achieve precision control of a soft hydraulic actuator, it may be necessary to implement

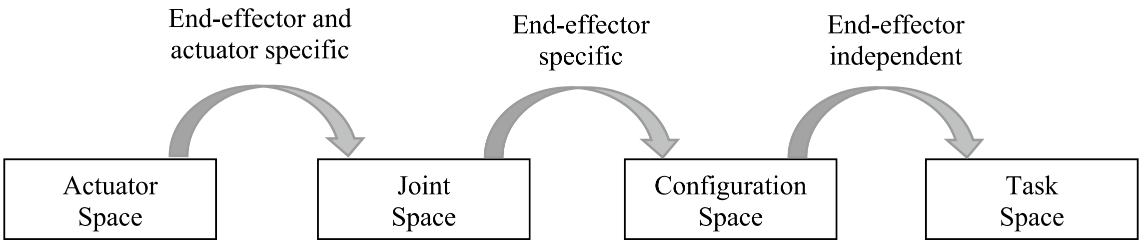

Fig. 1 Operational space of soft robot end-effector [69]

a relatively complicated feedback controller. In addition, inertia of the fluid and its friction limit the bandwidth of the controller to below 1 Hz [72]. Pneumatic control is more attractive for soft robots, since hydraulic control is more difficult to setup, operate and maintain. Pneumatic control provides a natural compliance matching feedback system [73]. Other control considerations include weight and cost. Hydraulic control systems are generally heavier and more expensive than pneumatic systems [72].

The inverse kinematics technique proposes a different solution for modeling and controls. Either a modal approach or a Jacobian approach is used based on a non-constant curvature assumption [74, 75]. Task-space motion control is a firm notion in robotics in that acceleration and force-based methods are commonly utilized [76]. This technique shows some potential for soft robots. It is usual in task space control methods to transfer the motion in a space suitable for the task. The control of the end-effector of a serial kinematic chain in Cartesian space is one of the foremost applications of task space control methods [77].

3.2 Model-free control methods

Soft robots are difficult to model because of their nonlinear nature. Behavior-based systems (BBS) for controls bring fast reaction times for complex tasks. The distributed nature of BBS covers the needs of the distributed structure of soft robots to a large extent [68, 78, 79].

Polymer gels combined with magnetic fluids (also referred to as ferrofluid) provide a media for soft robot's controls. Fluidic robots can be controlled or immobilized using magnetite particles at nano-size mixed in the base fluid [80]. The magnetic gels deform in a different manner, depending on the mode of immobilization. The characteristics of the magnetic fluids can be adjusted by the beamed magnetic field, and it results in (1) swelling of the interface, (2) levitation, (3) immobilization of the liquid, and (4) structural change of magnetic fluid [81–83]. This approach enables the manipulation of a soft robot using a variety of control techniques [84, 85].

Morphological computation and embodied intelligence are recent concepts for model-free controls of soft robots [86]. In these techniques, the soft robot complex interaction with the environment is not based on numerical or analytical models. The physical interaction is added to the robot's control by learning from experience. This approach is similar to how human brain learns from interaction with objects, and it has some similarity with BBS controls [87]. The robot's controller learns by identifying the correlation between the actuation and sensor data, and the morphology of the actuator interacting with objects [88].

Neural networks are among the list of good candidates for training soft robots to correlate actuator configurations to actuator inputs [89]. [90] is among the first who studied the inverse kinetics problem of a non-constant curvature actuator using neural networks. They proposed a neural network to learn the inverse kinetics of the soft actuator in three-dimensional space. Based on this trained model, a feed-forward neural network was able to correlate the actuator tip position and the applied forces to the cables without a model.

4 Actuation of soft robots

Actuation is an important design consideration for biomedical soft robots. Actuators are mechanical devices to induce strain into a system for generating movements or changing shapes. Traditionally, robotic actuations operate based on fluidic (pneumatic and hydraulic) or electric principles. For soft robots, these actuators may not be suitable, since size, weight, and materials' stiffness limit the usability.

Soft actuators mimic the actuation methods observed in biology, from an octopus arm to human tongue, but scientists have been unable to replicate biology thus far [91–93]. Soft actuators are made of natural and synthetic materials, and they work in response to various actuating stimuli. Table 1 shows the classification of actuators based on the actuation mechanism and the materials used. This paper discusses several different types of actuation that have potential use for soft applications including the advantages and disadvantages of each type.

Table 1 Classification of actuators based on stimuli and the materials used

Actuation type	Actuation mechanism	Materials
Variable-length tendon	Tension cables	Passive metals or polymers
	Shape memory alloys	Electro-metallic [94]
		Magneto-metallic [95]
	Piezoelectric	Electro-ceramic [96]
Polymers	Electric	Dielectric polymers [97]
		Liquid crystal elastomers [98]
		Electro-viscoelastic elastomers [99]
		Ferro-electric polymers [100]
		Electro-strictive elastomer [101]
	Ionic	Carbon nanotubes [102]
		Conductive polymers [103]
		Ionic-polymers [104]
		Ionic polymer-metal composite [105]
		Electro-rheological fluids [106]
Fluidic	Hydraulic	Passive metals or polymers
	Pneumatic	Passive metals or polymers

4.1 Variable-length tendons

Variable-length tendons can be classified as tension cables, shape memory alloys (SMA) and piezoelectrics. Tension cables are among the oldest techniques used for actuation. These actuators are embedded in the robot to apply a controlled force to deform parts in a desired way. Recent applications of this actuation is limited, since the integration of hard cables with a soft body is challenging. Among the recent studies, a soft actuator made from silicone was developed to mimic an octopus inspired arm using cables [107]. Cheng et al. [108] used tension cables driven by spooler motors to achieve complex manipulator configurations of a granular media.

SMA is another method to achieve actuation [108–111]. A SMA works by utilizing a material's thermal expansion property [112]. When selecting an alloy, often materials with high thermal expansion are desired [113, 114]. An easy method to heat the SMA is by inducing an electrical current and using the material's electric resistance to create heat. This in turn causes the material to deform [115]. An alloy with higher thermal resistance results in a quicker response time [116]. One way to increase resistance and the rate of temperature change of an alloy is to decrease the cross-sectional area [117]. However, this creates several drawbacks that hinders the SMA's versatility.

First, for a smaller SMA the ambient temperature must be either closely monitored or controlled entirely. Since SMAs are sensitive to temperature change, any external temperature change would affect the degree of actuation rendering the usefulness. Second, a small cross-sectional area of the material limits the maximum load to sustain. Despite these limitations, SMAs can still be useful if the required load is small and they operate in controlled-temperature environments.

Curved SMA actuators are capable of larger deformations with the same cross-sectional size as straight actuators. A novel design of a simple gripper uses curvature to lift objects. The curved gripper design has a lifting force nearly three times larger than the straight gripper. The actuator can be used to tailor the force and maximum deformation for the desired shape deformation [118].

A recent design is “GoQBot”. This design is a worm-like robot with an actuation rate smaller than 100 ms. The robot achieves rolling motion by using the deformation of the coils of SMA [119]. The rigidity of the coils of a SMA is a restricting factor for the movement of the robot.

Since the cooling time of an electric SMA limits its dynamics, a magnetically controlled SMA is considered as an alternative to generate motion and force. These materials deform in a magnetic field with shape changes up to 15% and response times of milliseconds [117, 120]. However, their applications in biomedical field are currently limited due to the requirement of having a magnetic field to initiate actuation mechanism [121].

Another intriguing method of actuation is piezoelectrics [122]. Actuation mechanism is similar to a SMA alloy in that a current must run through the material to create mechanical strain. This method of actuation offers many of the same advantages as SMAs. Using this concept, a team of researchers developed a new design for endoscopes by fabricating a robot that at its largest is no larger than 30 mm [123]. This robot is small enough to swallow by a human without any harm while passing through the patient's digestive tract. Figure 2 shows a schematic view of this robot.

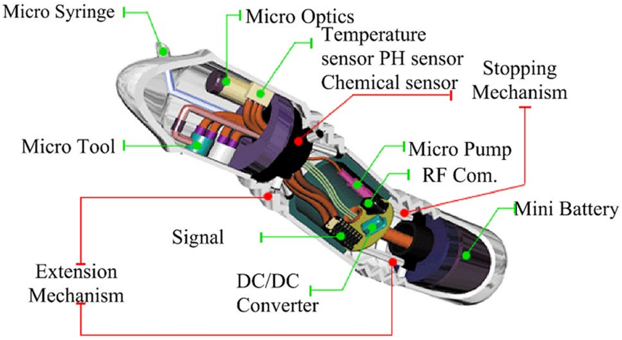

Fig. 2 Detailed view of the flexible piezoelectric powered robot [123]

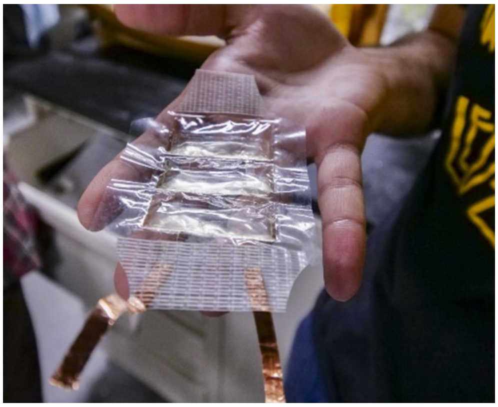

Fig. 3 A view of the hydraulically amplified self-healing electrostatic actuator [129]

The advantage of this actuator over SMAs is its independency to changes in temperature for actuation. These actuators do not have to operate in controlled environments. Piezoelectric actuators also have more rapid response times compared to SMAs. However, these actuators have their own drawbacks. The most considerable limitation is their limited elongation. These actuators do not have the capability to elongate more than 25% to 30% of their original length. While these actuators fit the need for some designs, their shortcomings may limit their wide applications for biomedical soft robots [124].

4.2 Polymer actuators

Polymers actuators are ideal actuation mechanisms for biocompatible soft robots. They are classified into two broad areas of electric and ionic polymers. Polymer gels are among actuators that accept a wide variety of stimuli such as pH, salt, solvent, thermal, photovoltaic, magnetic and electric as input [125–127]. An electric-responsive fluid gel is among the best options for biomedical applications, since they have fast actuation times. Dimensional change of the gels was observed first in 1965 using polyvinyl alcohol fiber-containing platinum powders [128]. The fiber expands when a negative voltage is applied (alkaline solution due to evolution of hydrogen), and it shrinks with a positive voltage since the solution becomes acidic.

A recent electric polymer design is the hydraulically amplified self-healing electrostatic (HASEL) actuator as shown in Fig. 3 [129].

These actuators rely on a chemical that tenses up once a voltage is applied as presented in Fig. 4. They represent a breakthrough in the field of soft robotics, because these actuators are the closest replication to a human muscle.

These actuators withstand a strain of 0.3 MPa similar to that of a human arm muscle. They are compliant enough to lift an egg softly and without puncturing the shell. Since these actuators operate by an applied voltage, the voltage can easily be controlled to fine tune the degree of actuation. They also boast extremely fast response times of 0.5 s for full actuation cycles. The limiting factor for these actuators is upscaling and shaping them to the desired geometry.

Ionic polymer-metal composite (IPMC) actuators with a chemically coated Nafion membrane are also good candidates for soft applications. IPMC has a compliance matching property to human body, and it is suitable for downscaling with low operational voltage (0.5–3 V) [130, 131]. Carbon nanotubes and ionic liquids are shown to have fast-moving rates at low voltage requirements. The actuator is fabricated by sandwiching the ionic gel electrolyte layer with the nanotube sheets. They show significant deformation capabilities in quick response times (4 mm per 0.05 s) as shown in Fig. 5. The applied voltage is low, and they have high durability for up to 10,000 times continuous actuation [132].

4.3 Fluidic elastomer actuators

A versatile material for biomedical application is elastomer. Elastomer actuators are not by any means new [133], but they are particularly useful for applications such as hand prosthesis [134]. Elastomer actuators operate in a similar fashion to SMAs. They both operate by undergoing a controlled and measured volume increase. A SMA uses materials' thermal expansion property to deform, and an elastomer actuator uses materials' mechanical flexibility to expand. The expansion is uniform, and it can be controlled in a variety of ways by restricting the motion.

A significant advantage of elastomer is its customizable modulus of elasticity. This feature is important because one of the main advantages of soft robots over traditional robots is the concept of compliance matching. Compliance matching means that the two contacting surfaces should have similar mechanical rigidity to evenly distribute the internal load and to minimize the concentration of interfacial stresses [19]. Because the rigidity of elastomer is customizable to

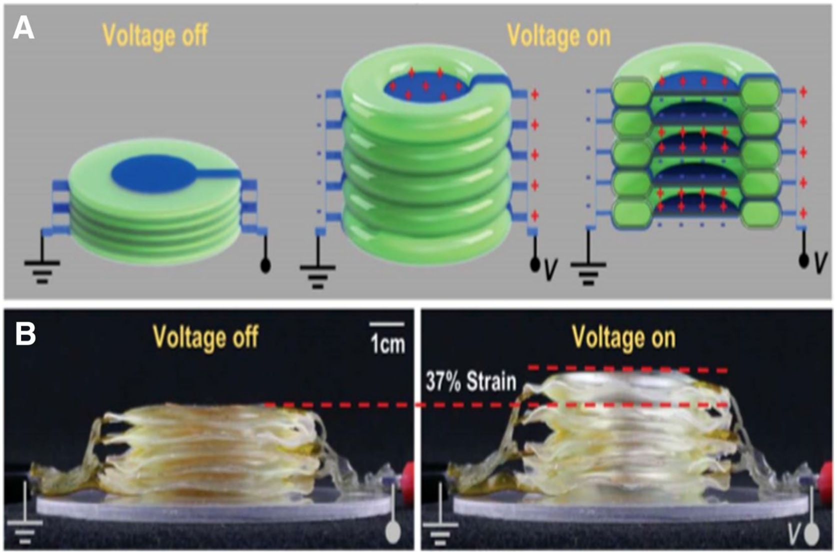

Fig. 4 HASEL actuator behavior before and after applying a voltage [129]

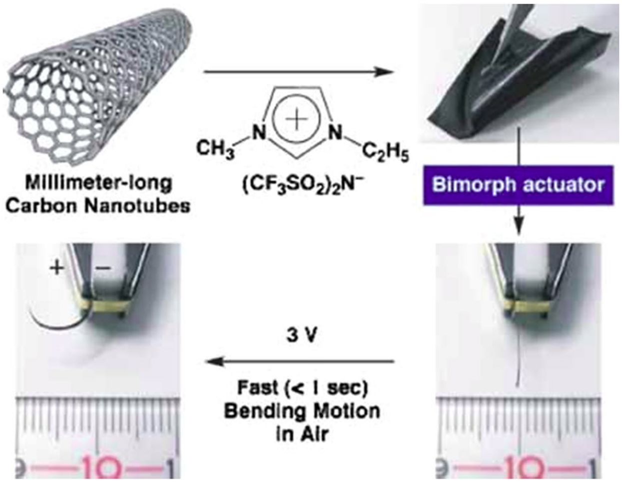

Fig. 5 Detailed and assembled view of the low-voltage ionic fluid and Carbon nanotubes used as a fast actuator [132]

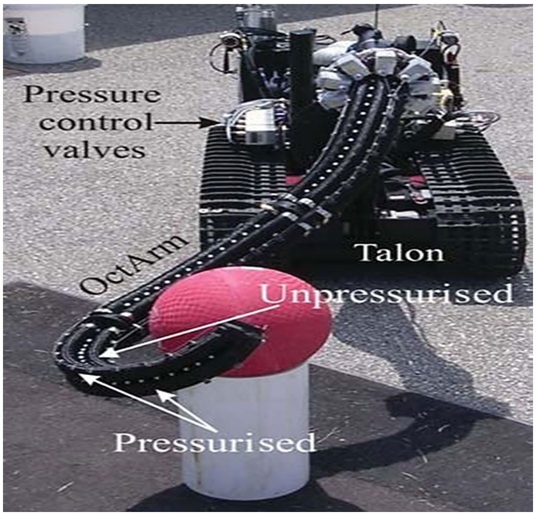

Fig. 6 OctArm VI on a mobile carrier (TALON) grasping a ball [91]

that of biological tissues, it can be used in any number of soft robotic applications as a cost effective solution.

Some simple deformations with this kind of actuation are bending, axial elongation and torsional deformation. These motions can be easily combined to create more complicated movements [91]. Bending can be accomplished in several different ways. For bending to occur, one side of the tube must expand more than the other side. One way to do this is to link two or more hydraulic or pneumatic actuators side-by-side to form a composite actuator. By increasing the pressure unequally in the sub-actuators, the composite actuator would bend toward the side with lower pressure. One example of this method is the OctArm VI shown in Fig. 6 [91].

A simpler method to achieve bending is to make one side of the actuator inextensible. This bending can be achieved with only one control element per actuator. This approach modifies the materials' composition of a single side of the actuator by either using a less elastic silicone rubber, or mixing different materials to create a heterogeneous body. An easy method is to adhere a layer of inextensible material such as paper, tape or fabrics to the actuator. In this way, as the actuator inflates, it bends toward the inextensible side. Since elastomers are thermally and electrically passive materials, their use in robotic applications is challenging. This passiveness means they cannot be actuated by a change in their temperature or electrical current similar to SMAs or fluid gels. Currently, there are several ways of actuations under development for elastomers.

One particularly interesting method is mixing the rubber with ethyl alcohol and embedding a resistive wire within the body [135]. This method uses the expansion of alcohol as it transitions from liquid to gas to actuate the rubber. This method is inexpensive to manufacture and the materials exhibit extensive deformation capabilities without compromising the integrity of the rubber. A similar way of achieving high-speed actuation is the explosion of a mixture of oxygen and methane to create a rapid pulse of pressure [50]. While an explosion can create a rapid motion, it is not easy to control this motion for precise applications. Therefore, there is still a significant amount of research needed before these methods would be practical for biomedical applications.

Building on the concept of an inextensible layer, another bending technique uses a network of pneumatic channels molded into the actuator [136]. These channels are carefully designed so that within the actuator there are small chambers. As the air pressure is applied to these chambers, they push against the adjacent chambers to distribute the effect of pressurization. Figure 7 shows the internal architecture of this design.

Another method to enable bending involves creating a silicone rubber tube with an inextensible layer, and then wrapping it with a reinforcing fiber [137]. This reinforcing fiber serves to restrict the motion in several ways. It prevents the actuator from expanding too much to prevent materials failure. Depending on the fiber angles used in the design, the actuator exhibits different motion. By combining the inextensible layer and the winding direction of the reinforcing fiber, it is possible to passively design a single actuator that exhibits complex behavior as depicted in Fig. 8.

This method is used for a portable and assistive soft robotic glove to augment hand rehabilitation for individuals with functional grasp pathologies. The robotic glove utilizes soft actuators consisting of molded elastomer chambers with fiber reinforcements that induce specific motion under fluid pressurization. These soft actuators are structurally tailored to support a range of motions of individual fingers. They demonstrate the ability to generate the desired motion when pressurized. To regulate the pressure of the soft robotic glove, a control hardware system is used. This system uses fluidic pressure sensors and the hydraulic actuators in closed-loop controls. Demonstration of the complete system was performed to evaluate the ability of the soft robotic glove to carry out gross and precise functional grasping. Compared to existing devices, the soft robotic glove has the potential to increase user freedom and independence through its portable waist belt pack and open palm design [137].

5 Fabrication of soft robots

Due to the compliance matching requirements, soft robots need novel fabrication techniques. Unlike the uniform material properties of rigid-bodied robots, soft robots can be comprised of numerous materials with variable stiffness properties [9, 138]. Shape deposition manufacturing (SDM), smart soft composite casting (SCC), and additive manufacturing are among formal manufacturing techniques for soft robots [139–141]. However, many soft robotic designs employ a mixed manufacturing technique.

As mentioned in Sect. 4, the SMA is a simple and compact option for actuation. [142] replicated the movement of the human finger using two actuators, each consisting of two 0.3 mm diameter one-way SMA wire. The wires were inserted through both ends of a stainless-steel tube, and they functioned as a director and a method for heat dissipation.

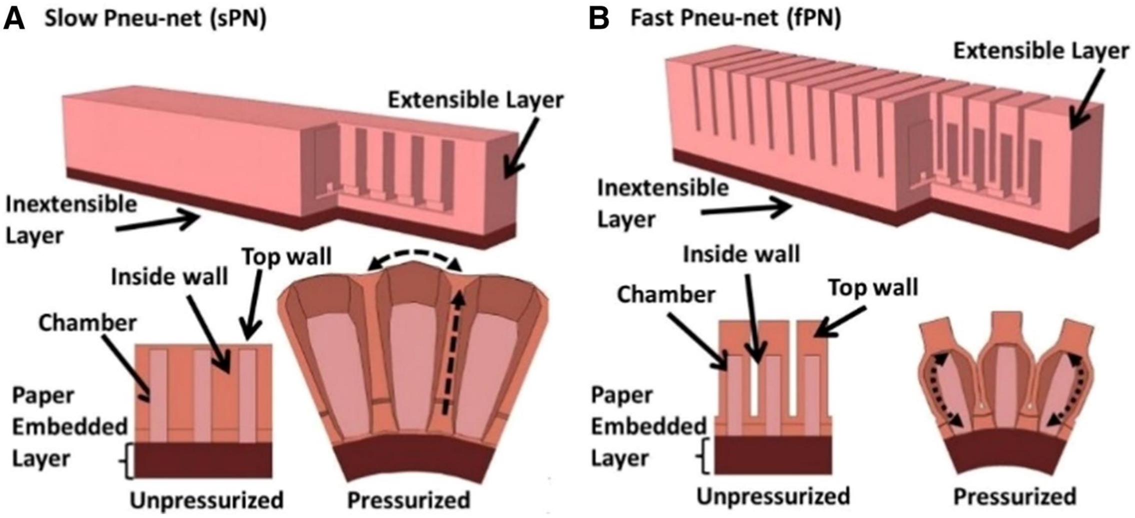

Fig. 7 Detailed design of the Pneu-nets actuator. This design can either be used for slow or fast actuation depending on different used topologies [136]

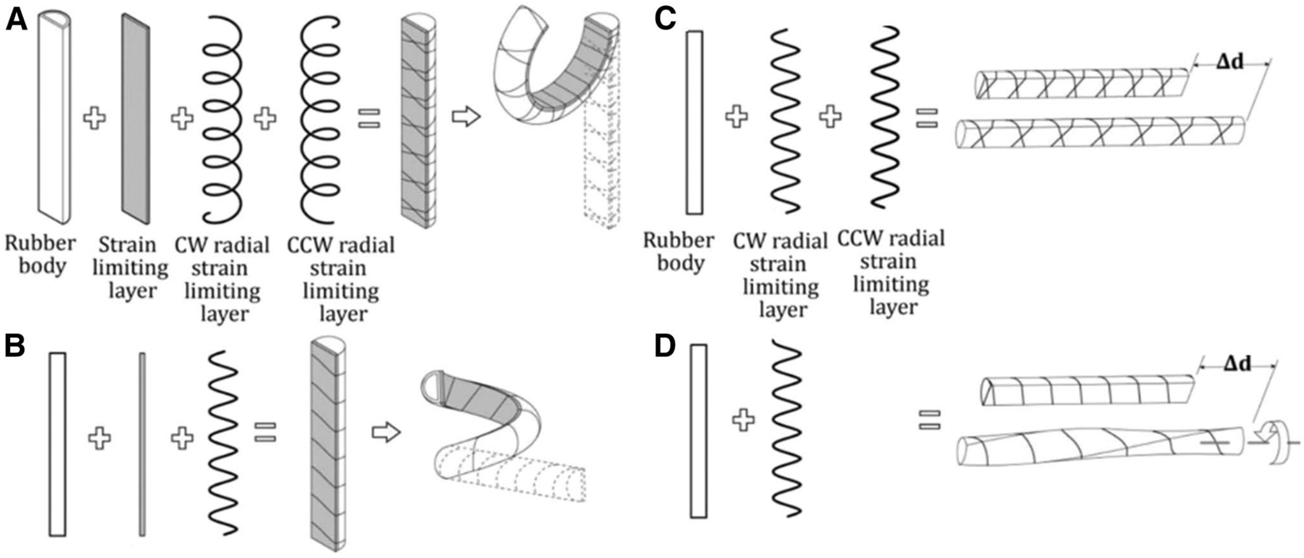

Fig. 8 Detailed view of soft actuator components before and after actuation [137]

The two actuators were used simultaneously to mimic the flexion and extension of a soft finger.

The electro-rheological fluid uses only a dielectric liquid to create an effective soft actuator. The HASEL actuator is an example of an application of this actuation type. The HASEL actuators are fabricated in a donut shape or a planar shape to distribute the hydraulic pressure within the elastomer shell. The elastomer shell of the actuator is made up of the silicone compound polydimethylsiloxane (PDMS). The liquid dielectric consists of a bio-based natural ester coolant typically used in transformers. The electrodes are comprised of an ionically conductive polyacrylamide hydrogel. The elastomer shell is filled with the liquid dielectric and the shell is covered with a pair of electrodes. When voltage is applied, an electric field is created through the liquid for actuation.

The reason that the pneumatic actuator is the most popular actuator type in the soft robotic industry is its simple fabrication. As shown in [137], pneumatic actuators can be fabricated with reinforcing layers such that the body is mechanically programmed to replicate the movements of a gripper. To fabricate this actuator, first, the rubber tube was molded using a 3D printed mold, which includes grooves to set the reinforcement layers. Flat and radial reinforcements consisting of high durometer rubber, woven materials or non-woven materials were applied to the exterior of the rubber body as a strain-limiting layer.

The flat layer was applied to the flat side of the body, and the radial reinforcements were wound around the body. The direction in which the radial reinforcements were wound (clockwise, counter-clockwise, or a combination of the two) determines the range of motion of the actuator. To complete the assembly, a thin layer of rubber encapsulated the entire body and reinforcements to create a robust actuator.

Another method of fabrication of pneumatic actuators is to combine two or more parallel pneumatic tubes made up of a mesh or silicone as shown in Fig. 9 [143]. The wall thickness of the tubes is chosen to provide stiffness and sufficient area to meet a desired load capacity and curvature based on the applied pressure. The pressure difference between the tubes determines the directional motion of the actuator.

Due to the liquid nature of an elastomer at its fluid state, it is possible to fabricate an actuator using additive manufacturing. The main challenge concerning pneumatic

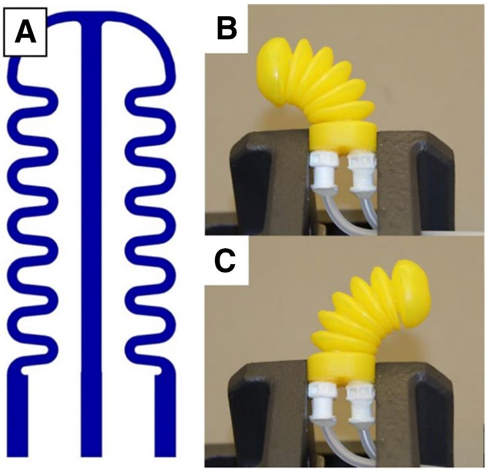

Fig. 9 Combination of parallel tubes to achieve different motions, **a** sectional view of the antagonistic actuator **b** right chamber under pressure. **c** Left chamber under pressure [143]

actuators and additive manufacturing is the ability to construct a mechanically heterogeneous structure. There are multi-material additive manufacturing processes capable of printing both metal and polymers. However, the structural reliability of the product is uncertain [144]. Because of this, there are pneumatic actuator designs created to use homogeneous elastomer structures. As shown in [145], elastomer bricks can be joined to form a hollow tube that is actuated by inflating. The bricks can be easily fabricated into any shape making use of a 3-D printed mold. A homogeneous brick can be made by pouring a single material into the mold, or multiple materials can be layered into the mold to create a heterogeneous brick. The combination of bricks constructed of different materials can be glued together to create an inflatable actuator with controllable deformation as shown in Fig. 10.

6 Application of soft robots in medical field

This section discusses some applications of soft robots in the area of biomedical engineering. A soft robot capable of compliance matching with biological structures has potential applications in artificial muscles, muscle alternatives, prosthetic devices, catheters, stents and surgical instruments. Soft robots also have the potential to revolutionize the field of physical therapy and rehabilitation [146–149].

The body functions are currently restored by provoking movements in a joint or muscle [150]. The gel, elastomer, electroactive polymers and conductive polymers actuators are of high potential in this field [151–154]. Severe injuries such as car accidents and work-related accidents may need a full muscular implant in the recovery process.

New soft actuators are under development to serve as artificial muscles for facial paralyzed patients, ptosis patients and grasping capability in neurological rehabilitation [155–157]. Ventricular assistance devices (VADs) have been already developed to function in place of failing ventricles in the heart to improve heart deficiencies [158].

Soft robots made of elastomers are used to surround the heart to provide ventricular assistance [159]. Elastomer actuators are flexible, thin and light, and they operate on low voltage with fast reaction times. These characteristics provide great potential for polymer actuators in medical applications. Polymer actuators are currently in use for catheter driving. This system is installed on a catheter and is activated by applying a small voltage to the membranes [160, 161].

Localized drug delivery systems are developed utilizing drug-loaded nano-capsules for fulfilling precision drug-delivery. This type of drug-delivery devices is useful for anti-inflammatory, anti-thrombotic, anti-neoplastic and anesthetic agents. The critical component of the drug-delivery device is an electroactive-polymer-actuated stent that shrinks and expands, respectively, by applying a voltage and contacting a body lumen [162].

Conductive polymers are in use for making the balloons that are utilized in percutaneous transluminal coronary angioplasty (PTCA) treatments. These balloons re-open the occluded coronary artery when they inflate [163, 164]. Conductive polymers are also useful for aortic aneurysm coil to prevent the rupture of thoracic or abdominal aortic aneurism. Conductive polymers have applications in expanding and contracting the filter that catches the dislodged blood clot [165]. Several medical pumps are made of polymer actuators such as drainage pumps [166] and the pumps used for controlling the blood pressure [167].

7 Limitations of soft robots

The up and coming field of soft robotics has many applications that can improve daily lives, promote efficiency and even keep people alive. For a field of study that has near endless amount of capabilities, soft robots possess their fair

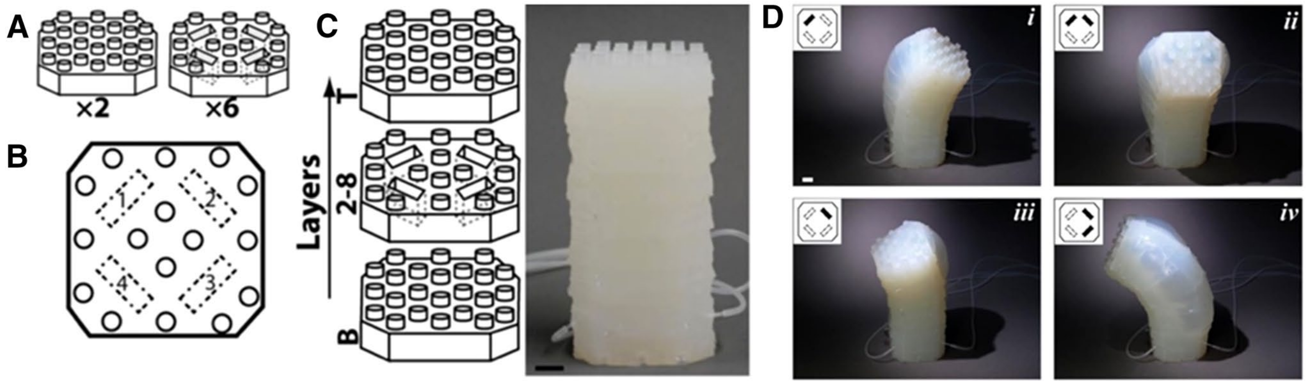

Fig. 10 Assembly of the click-e-bricks using a multi-chamber soft design [145]

share of limitations. Engineers, physicists, material scientists and physicians are continuing to address these shortcomings with hopes of changing the world with this innovation.

Miniaturizing and making soft robots smaller and lighter is the primary goal of design teams. The first priority is a power source. Typical soft robotic systems that have been created so far are using batteries. The batteries that are being used have an energy density that is 10–100 times lower than the sugars and fats that power natural muscles [19].

The future discovery of a microscopic power source or even a bio-hybrid material could increase the biological compliance and create a dramatically lighter robot. Another discovery that would push soft robotics to the forefront of the industry is the development of microscopic actuators. In the human body, muscle fibers are an intricately woven system that actuate with multiple degrees of freedom. However, current prototypes are bulky and contain an actuator for each direction of motion that is desired. Developing actuators that overlap in performance capabilities are among the limitations of the present-day soft robots [168].

For the soft robot to completely model a biological structure, higher degrees of movement are needed. These movements are limited by the material properties and the number of actuators allowed. Developing a robot that could manipulate with infinite degrees of freedom using the present-day materials and actuators would result in an over-sized and inapplicable structure. The intended use of the soft robot ultimately determines the properties that the material needs to withhold.

Scientist are continuing the search for the new materials or combination of materials that allows the soft structure to be compliantly matched to biological structures. To compliantly match human muscle fibers, it is claimed that [169]:

1. strains need to be greater than 40%,
2. the body to withstand stresses up to 35 MPa,
3. the structure to operate with strain rates up to 500%/s,
4. have an energy density of 8 kJ/m^3,
5. the modulus of elasticity to be in the 10–60 MPa range, and,
6. operate with a cycle life of millions.

The materials that are available today match some of these properties, but none can fulfill all of them. A majority of the material properties that are used correlate directly to size and strength. The actuation material must withstand high stresses and strains, have a quick actuation time and be extremely efficient. The field of soft robotics needs materials that not only act as actuators but also serve as position sensors [170].

It is extremely difficult to design muscles with skin-like surfaces that have the ability to sense properties like pressure and temperature. This need initiates an entirely new field of research referred to as stretchable electronics. Designers have developed prototype electronics that could be integrated into the designs of soft robots. However, most of the designs are lacking the ability to stretch and high durability at low cost [171]. For the field of soft robotics to continue development, one material or combination of materials is needed to provide strengths, withstands strains and enable sensing of various properties. The human biological structure is the most intricate system, and it will not be easy to replicate for the years to come.

8 Outlook

Further development of soft robotics depends on the creation of advanced controls, accurate simulation and simplified fabrication techniques. The success of soft robots rely on the advancement of sensor and actuator technology as well. Further development in soft materials will provide alternatives capable of mass production and high performance. By addressing the limitations discussed in the previous section, the field of soft robotics will be able to expand rapidly [91].

Currently, pneumatic energy systems are being employed in soft robotics. In the future, the pneumatic systems could become completely dominating. As a result, the capability of the systems would increase [172]. A combustion-based energy system would be a good alternative as a fuel source. The use of methane and butane has been explored, but it has been determined that they react at a high speed and pressure for the current control technology to cope with. Therefore, alternative power sources should be studied or the system level should be improved so that explosive gases can be utilized.

Modeling soft robotic systems has proved to be difficult in that there are numerous degrees of freedom associated with soft robots. To model a soft robotic system, large deformation of the materials must be analyzed alongside the nonlinear kinematics of the actuation of the system. Several approaches are used so far to approximate the behavior of the system. However, the models remain complicated and the approximations leave the potential for large errors in the analysis. Novel models need to be developed to allow the study of soft robots in details and widen the capabilities for design.

In the field of wearable electronics, stretchable electronics are at the proof of concept stage. Currently, artificial E-skins are being tested in circumstances that involve interaction with humans or for the use of human-like robots. E-skins are composed of a pressure sensitive rubber and a grid of organic field-effect transistors. For the future, a new process to rapidly produce these products would allow for the mass production of wearable devices such as rehabilitation gloves. Further development of stretchable electronics will make them more useful in physical therapy and other human compliant situations [173].

For the medical field, the needs for biocompatible materials and systems continue to increase. Additional research into potential soft materials must be performed to uncover materials that can support living cells and tissues. As the development of new materials takes place, rapid prototyping processes are needed.

The goal of soft robotic design is to develop an autonomous and reconfigurable system that can morph between both soft and hard behaviors. New adhesion techniques are being studied and would lead to the ability to utilize autonomous morphing on larger commercial scales. This domain could grow in the field of micro-aerial vehicles and deformable sensors as well as medical and educational fields.

Tactile sensors and deformable electronics only have limited grid size accuracy. In the future, the grid size resolution needs to be increased so that they cover more extensive and more complex areas. In addition, the control of the sensors and electronics needs improvement to accommodate the finer grid sizes. By reducing the grid size, the electronics and sensors could be expanded to other applications as well [174]. Research shows that the biomedical robots are not yet developed enough for clinical applications. This limitation arises from issues such as long-term investment, usability and the gap between technology development and patient needs [175].

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Compliance with ethical standards

Conflict of interest All the authors declare no conflict of interest.

Human subjects This article does not contain any studies with human participants or animals performed by any of the authors.

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