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Soft Robot Review

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Abstract: Soft robots are often inspired from biological systems which consist of soft materials or are actuated by electrically activated materials. There are several advantages of soft robots compared to the conventional robots; safe human-machine interaction, adaptability to wearable devices, simple gripping system, and so on. Due to the unique features and advantages, soft robots have a considerable range of applications. This article reviews state-of-the-art researches on soft robots and application areas. Actuation systems for soft robots can be categorized and analyzed into three types: variable length tendon, fluidic actuation, and electro-active polymer (EAP). The deformable property of soft robots restricts the use of many conventional rigid sensors such as encoders, strain gauges, or inertial measurement units. Thus, contactless approaches for sensing and/or sensors with low modulus are preferable for soft robots. Sensors include low modulus ($<$ 1 MPa) elastomers with liquid-phase material filled channels and are appropriate for proprioception which is determined by the degree of curvature. In control perspective, novel control idea should be developed because the conventional control techniques may be inadequate to handle soft robots. Several innovative techniques and diverse materials & fabrication methods are described in this review article. In addition, a wide range of soft robots are characterized and analyzed based on the following sub-categories; actuation, sensing, structure, control and electronics, materials, fabrication and system, and applications.

Keywords: Biological systems, flexible materials, smart structure, soft robotics, soft structure.

1. INTRODUCTION

Biological mechanism and locomotion systems have inspired many robot engineers and scientists to study multifunctional systems [1]. Innovative and creative results from such research have organized a new field of robotics called soft robotics. Soft robots have distinguishable features compared to the conventional robots. Conventional robot's structures are made with high stiffness materials such as steel, aluminum, titanium, stainless steel, etc. These parts can be manufactured by mechanical machining tools including milling, lathe, computerized numerical control (CNC) machine, and are mechanically assembled. On the other hand, soft robots adopt hyper elastic materials for main body and moving parts such as polymer, rubber, silicone, or other flexible materials. These are manufactured using a three dimensional (3D) printer or 3D mold. Material stiffness of soft robots are often in the order of $10^4 - 10^9$ Pa corresponding with biological skin or muscle tissue [2]. Due to the differences in material and manufacturing method utilized, protection and stability strategies are contrasted with that of rigid-body robots. Conventional robots require complex protection or stability control algorithm whereas soft robots do not require such methods due to shock absorbing property of the materials used. For this reason, conventional robots are designed for specific tasks in controlled environments, while soft robots are made to perform in unstructured environments. Conventional robots are usually actuated by electrical motor, hydraulic pump or pneumatic compressor which is capable of producing force ranging from a few millinewton (mN) to meganewton (MN). However, one of the main disadvantages of soft robot is being unable to produce a large force owing to its elastic structure and usage of pneumatic compressor, shape-memory alloy (SMA), electro-active polymer (EAP), etc.

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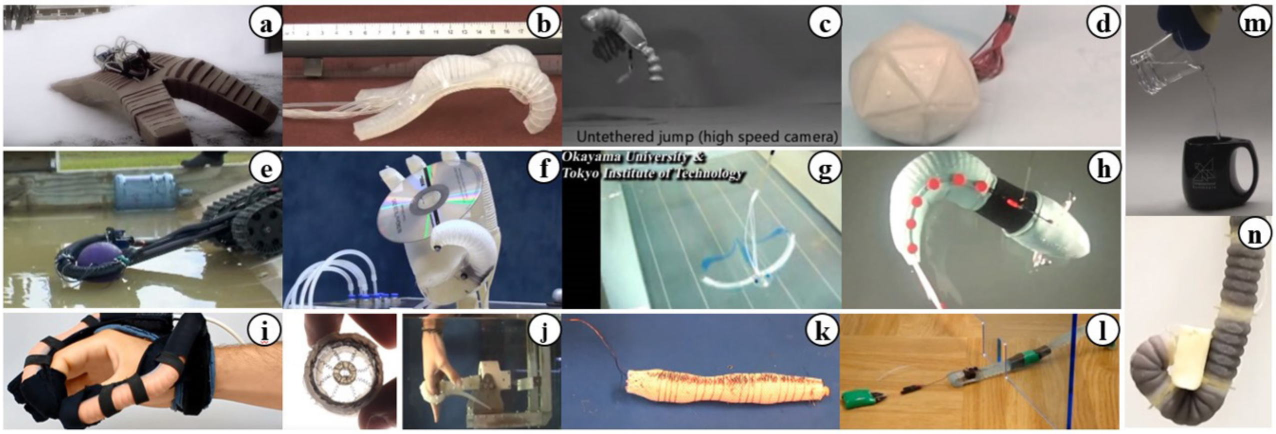

Fig. 1. Soft Robots. (a) A resilient, untethered robot [3]. (b) Multigait soft robot [4]. (c) Untethered jumping robot [5]. (d) Jamming skin enabled locomotion (JSEL) [6]. (e) OctArm [7]. (f) Compliant and underactuated robotic hand [8]. (g) Manta swimming robot [9]. (h) Hydraulic autonomous soft robotic fish [10]. (i) Soft robotic gloves [11]. (j) Octopus robot [12]. (k) Meshworm robot [13]. (l) GoQbot [14]. (m) Universal granular jamming [15]. (n) Jamming granular robot [16].

Despite this disadvantage, there are several advantages of soft robot using soft materials. It can interact with human and environment more safely than conventional rigid robot system by reducing the risk of injury to itself and surroundings from collision [2]. This allowed its application to be extended to a wearable devices and medical usage. In addition, soft robots have inherent benefits over conventional rigid robot system in gripping motion having simpler structure and control algorithm. Due to the unique features and advantages of soft robot, it has various application areas.

In the following sections, state-of-the-art researches on soft robot are categorized and analyzed based on the following sub-categories; actuation, sensing, structure, control and electronics, materials, fabrication and system, and applications. Then, specific issues regarding soft robot are discussed followed by suggestion of its future directions.

2. SOFT ROBOTS

2.1. Actuation

Conventional robots are actuated with rigid motors and various complicated mechanisms are realized by rotational and linear actuation systems. In contrast to the rigid-body robots with limited degrees of freedom (DOFs) of motion, soft robots have continuum deformation of the flexible body resulting in high DOFs. According to the previous studies [2, 17], most soft robots are actuated in one of three ways: variable length tendons, fluidic actuation, or EAP.

Variable-length tendons in the form of tension cables or SMA actuators may be embedded in soft segments delivering a controlled force to deform the segment in a desired way. An octopus inspired robot used silicone arm with embedded cables to replicate the functionality of muscular structure of the octopus arm [18]. When tension is applied to cables using spooler motors, the granular media such as grained coffee grabs the target object by granular jamming [19]. A meshworm robot, which is inspired by peristaltic locomotion of Oligochaetes, uses nickel titanium (NiTi) SMA as its mode of actuation [20]. GoQBot is a caterpillar inspired soft bodied rolling robot and also utilizes SMA coils which yields larger strain than the straight form [21]. Relatively small strain produced by SMA has been pointed out as a disadvantage, but it can be overcame by using spiral-shaped SMA. Another soft robot inspired by mechanical characteristic of octopus uses both tension cable (longitudinally) and spiral SMA (transversally) [22].

Fluidic actuator inflates channels within the soft body to deform the structure in a controlled manner [2]. As one of earlier versions of fluidic actuator, pneumatic artificial muscle (PAM) was suggested. PAM, also called McKibben actuator, is a flexible linear soft actuator consisting of deformable elastomer tubes encased by fiber sleeves [23,24]. Progressively, more soft robots using fluidic elastomer actuator (FEA) are reported. FEA is a novel type of highly deformable and adaptable soft actuator. It has synthetic elastomer layers and deforms by pressurized fluid expanding the embedded channels. This type of architecture is often called Pneu-Nets (PN). Little or no additional energy is required to hold its shape once the actuator is deformed by pressure. Pressure used in FEA can be either pneumatic or hydraulic. Due to the omnipresence, less inviscid and lightweight nature of air in the environment, pneumatic systems are often preferred over hydraulic systems. A recent study [25] reported resilient quadrupedal soft robot, it can adapt to various environmental conditions. It is an advanced version of its previous study [26].

The new model employs a modified PN architecture for more rapid and stable actuation differentiating from its previous design [27]. A different quadrupedal soft robot model can camouflage itself in an environment through altering its color, contrast, pattern, apparent shape, luminescence, and surface temperature [28]. It also uses PN design for pneumatic pressurization in an independent network of micro-channels embedded in highly extensible elastomers. A snake inspired soft robot consists of four bidirectional fluidic elastomers [29], and it provides serpentine locomotion despite some rigid components such as passive wheels. Another pneumatic-based locomotion is seen in a robot with jamming skin [30]. The locomotion is provided by deformation of unjammed cells caused by pneumatic expansion of a volume variable actuator inside the soft robot.

In some soft robots, not only omnipresent air but also other chemicals were used to power the actuators. The chemical decomposition of hydrogen peroxide into oxygen gas in a closed container was used to self-regulate the actuation pressure [31]. In other cases, explosive actuators using butane gas are utilized for directed jumping motion [32]. The FEAs have been used not only in locomotive robots but also in manipulators. One of early models of FEA, actuated with pneumatic pressure and channels made from rubber, was suggested in the early 1990s [33]. It had three DOFs, pitch, yaw, and stretch, which make it suitable for robotic mechanisms such as fingers, arms, or legs. OctArm continuum manipulator was pneumatically actuated and tested in both open-air and in-water environments [34]. A gripper implemented with lithography techniques and PN architecture have been reported previously [35], and a hand robot for dexterous grasping with modified version of PN called PneuFlex was also reported [36]. Another research focused on wrist torsional motion by helically arranged tubes rather than finger grasping [37]. As for another case, the previously mentioned quadrupedal soft robot [26] was modified to conduct both locomotion and grasping [38]. Another type of pneumatically actuated soft robot, a manta ray inspired swimming robot was reported [39]. It tested various cross sections of bending pneumatic actuators and developed manta swimming robot based on the results.

Hydraulic actuation is not as common as pneumatic but can produce a larger force. A soft robotic fish capable of 3D swimming, such as forward swimming, diving, and turning, was reported [40]. For medical purpose, a soft robotic glove for at-home rehabilitation was introduced [41]. It contains hydraulic pumps and a water-reservoir for actuation.

EAPs are biocompatible polymers that exhibit a change in size or shape when stimulated by an electric field. First proposed by Wihelm Rontgen in 1880s, EAPs are classified into two categories: electronic EAP and ionic EAP [42]. The electronic EAPs generally require high activation fields (> 150 V/μm) and hold the induced displacement when a DC voltage is applied. The electronic EAPs have high energy density as well as rapid response time in the range of milliseconds. In contrast, ionic EAP such as ionic polymer-metal composite (IPMC) requires low actuating voltages (< 5 V) [42]. Additionally, it has a natural bi-directional actuation property deforming in different direction based on the voltage polarity [43]. IPMCs are advantageous due to its ability to achieve large deformation with relatively low electric field (< 10 kV/m) and therefore are more efficient and safer [44]. Besides, they have low power consumption, and demonstrate rapid actuating response (> 10 Hz in water). Also simple actuator structure enables miniaturization of soft robots. The ionic EAPs have limitation of having to operate in wet conditions in solid electrolyte, and therefore require encapsulation or protective layer in open air condition [43]. They produce relatively lower bending force than electronic EAPs.

Since IPMC was first discovered in 1990s, its use in soft robots has been investigated [17, 42]. When driving voltage is applied, the IPMC membrane bends toward the anode because the hydrophilic positive ions or cations move toward the cathode. Considering the fact that IPMC works in the cantilevered form, the geometric properties of the beam, such as thickness, width, and length, should be tuned to achieve desired level of force and deflection [17]. Previous studies investigated about IPMC based bioinspired soft robots such as snake-like swimming robot [45, 46] and multi-DOF micro-robot manipulators [47, 48]. Whereas early studies used simple strip-shaped IPMC, which only enables simple bending motion [49, 50], patterned IPMC can provide multi-DOF motions. It enables individual control of each segment of IPMC and is more efficient in performing complex motions, such as snake-like wavy motion.

As reviewed in this section, actuation methods used in soft robots can be classified into three types, variable length tendon, fluidic actuation, and EAP. Actuation approaches using variable length tendon can be subcategorized into tension cable based and SMA based methods. Fluidic pressure actuation system can be further subcategorized into pneumatic and hydraulic actuation. In case of EAP, it can be classified into electronic and ionic types. Every approach has unique advantages compared to the others, and have demonstrated notable performances in individual researches. Especially, pneumatic pressure based soft robots has wide application areas and reported frequently. The major advantages of each actuation method are summarized in below Table 1.

2.2. Sensing

Sensors allow proprioception of robotic hardware but the deformable characteristic of soft robots prevents the use of many conventional sensors including encoders,

Table 1. Advantages of three actuation approaches.

Actuation approach		Advantages
Length variable tendon	Tension cable	- Use of conventional motor in external platform for actuation
	Shape-memory alloy (SMA)	- Easy manufacturing and programming - A spiral shaped SMA capable of 300% deformation (Beam shape: 5-8%)
Fluidic actuation	Pneumatic	- Omnipresent air - Environmentally benign - Light weight - Less inviscid (less time delay)
	Hydraulic	- Larger force compare to pneumatic actuators - Ability to be implement in untethered in-water soft robots
Electro-active polymer (EAP)	Electronic	- High energy density - Larger force compare to ionic class - Rapid response time in the range of milliseconds - Long operation time
	Ionic	- Low actuation voltage - Large bending displacement - Bi-directional actuation is possible

strain gauges, or inertial measurement units [2]. Thus, alternative sensing methods are preferred over the conventional sensors. Contactless or low-modulus sensors can be the alternatives. Sensors with low modulus ($<$ 1 MPa) elastomers along with liquid-phase materials are appropriate for proprioception of curved structure and this type of sensors apply a small impedance change to soft robot hardware [2]. These types of soft sensors are conventionally manufactured by soft lithography where thin elastomer layers are patterned with microfluidic channels. These microfluidic channels are filled with liquid conductors, such as eutectic gallium-indium [51–54] and conductive carbon grease [55]. Deformation of the structure causes a change in geometry of the channels and their electrical resistance and through measuring the change in resistance, strain can be calculated. This type of sensors can be tuned by modulation of channel geometries and can measure various types of strains [51–53]. For the fabrication of the sensors, various approaches such as mask deposition of the conductor [56], and direct 3D printing of conductive material [55], have been suggested recently. As for the sensing methods, not only resistive changes according to deformation of sensor's hardware but also capacitive [54] and inductive changes [57, 58] can be used. The capacitive approach is applied to elastomer layers patterned with microfluidic channels, and the inductive change is used to measure displacement of the McKibben actuators. The geometry of conductive fibers surrounding McKibben actuator changes as it contracts or stretches, and the inductance of the structure changes with it.

IPMC, which was described in the actuation section, is a smart composite material exhibiting characteristics of both actuators and sensors (energy harvester) and this property makes it unique [42]. IPMC based sensors are also employed in soft robots [59]. IPMC demonstrates a linear voltage output when quasi-static displacement is placed at the tip of IPMC. Besides, IPMC also responds to dynamic stimulus such as impact or shock loading, and a damped electrical variation is observed [59,60]. Although both IPMC and piezoelectric sensor can detect mechanical stimulus, IPMC has higher sensitivity. Moreover, IPMC is suited for sensing any modes of deformation such as bending, tension, compression, torsion and shear.

Although, the application of soft sensors in soft robots is not very prevalent, they are an important component for attaining accurate control of soft robots. Moreover, the applicability of the soft sensors extends beyond the soft robot. Recently in eHealthcare areas, unobtrusive sensing and wearable devices are receiving much attention [61], and flexible and stretchable soft sensors with low impedance are suitable for this purpose.

2.3. Structure

The structures of soft robots are unlike those of rigid-body robots. This is because soft robots are usually manufactured using soft materials and therefore are not suitable for exploiting conventional electric motors. In this sense, researchers have developed several special structures for soft robotic systems such as those made up of soft materials, mainly silicone rubber and SMA, soft materials with medium enclosed in them.

For example, GoQBot is a soft robotic system with the structure based on silicone and SMA [21]. This system consists of a flexible silicone body and two tensile actuators. To generate forward displacement, this system is divided into two sections: an anterior part and a posterior part. Meshworm is one another case which uses this type of structure [20]. To achieve sequential antagonistic motion, this system mimics circular and longitudinal muscle structure and arrangement of oligochaetes, and uses mesh materials and NiTi SMA. Lastly, an octopus soft robot also uses the structure based on silicone and SMA and engages in biomimetic [22]. The structure of this system directly mimics the muscle system of octopus. It consists of four longitudinal actuators and one radially allocated actuator, which represent four longitudinal muscle bundles and transverse muscles of octopus respectively and resemble the tissues.

Researchers have also developed soft robotic systems using some medium encased within the silicone material. Manta swimming robot is one of the kind [39]. To achieve two degrees of freedom of bending motion, it used silicone rubber which has two internal chambers. A soft snake robot also employs similar structure [29]. In this research, they designed and developed a snake-like robot system based on fluidic system. The proposed system consists of four fluidic actuator parts and passive wheels between every two actuator parts. A multigait soft robot is also developed based on this kind of structure [26]. One different feature is that it is composed of elastomeric polymers inspired by animal tissue. The proposed system consists of five parts which can be independently actuated by pneumatic valves. Based on similar concept, a soft robot gripper has been also developed [35, 62]. This gripper can be actuated based on pneumatic system. Since it used soft materials, it offers enhanced safety compared to a rigid system. Jamming skin enabled locomotion is a soft robotic system inspired by a different actuating system to the previous works described but shares similar structure [30]. It consists of several silicone cells and an expandable actuator, and is filled with fluid. The silicone cells can be divided into two types, jammed and unjammed cells. Similarly, a jammable manipulator using granular media was developed [19]. This robot is composed of five serial jammable parts. Unlike other granular systems, ground coffee has been used as granular media. Similarly, a universal robotic gripper, which can be integrated with a 6-axis robot arm as an end-effector, has also been developed [63, 64]. The structure of this system is quite simple. This system do not have many parts like other silicone and medium based system, it only has a single compartment filled with granular material.

As for other soft robotic systems, there are some systems which only use soft material for their actuating parts, not in overall systems. Soft robotic fish are examples of this kind of structure which mimicked fish's body [65, 66]. However, the system can be seen as a rigid robot system as a whole except for the part from dorsal section to anal section. This is due to the purpose of actuating its tail in order to provide force to navigate the entire body, like real fish does. SmartBird is another system which utilizes similar structure [67]. As it can be inferred from the name of the system, it mimics birds for developing a system capable of flying. Similar with soft robotic fish, most of its system can be considered as rigid-body system. However, it utilizes soft material on wings of the system mimicking material property of a real bird wing in order to achieve the better performance.

2.4. Control and electronics

Control methods used for soft robot can be classified into two categories, open-loop control and closed-loop control. The most representative philosophy of soft robots is to exploit material properties, in particular, softness. Because of this feature, it is important to consider compliance enabling the robots' body and functions to be suited to their environments. This aspect makes it difficult to implement suitable sensors or acquire a reliable dynamic model, based on which the controller can be designed. Accordingly, there have been many attempts to develop soft robots without using specific sensors or feedback control, which is referred to open-loop control. Whereas many problems are encountered for open-loop control using compensated input to determine output, closed-loop control enables more accurate and robust actuation of implemented systems. Through utilizing proprioceptive sensors, closed-loop control reflects the outputs of a system to make control inputs. With the dynamic model, it is possible to design an efficient controller which takes the characteristics of the system into account. In soft robot application, linear model based adaptive controllers [68, 69] were introduced. Additionally, model predictive control [70] for pneumatic actuation and linear quadratic regulator for SMA actuator were reported. Even though several cases of soft robot control have been reported, control still remains as the main challenge in soft robotics because most of the control approaches are not yet generally defined compared to conventional robots. Furthermore, there should be more progress on soft robot control for autonomous behavior, so that the robot can be used in multiple cases: high level tasks, cognition, and interactions with their environment. Online learning may help configure models or conduct tasks in unstructured environments where there are many uncertainties.

Soft robot electronics have employed rigid electronics to hold control algorithms and interconnect the systems' actuators, sensors, and power sources [2]. This rigid electronics is a mismatch with biological materials which are soft, elastic, and curved [71]. There has been a progress in electronics area that allows flexible and stretchable nature. This is also known as "stretchable electronics". Soft robots have barely incorporated a soft electronic system for all the soft robotic parts as of now but for enhanced performance and better suitability to the environment especially biological application, use of stretchable or flexible electronics is crucial.

Rigid electronics are either incorporated in soft robot itself becoming a part of the soft robot [25, 40, 66, 72, 73] or housed externally in a physically different location to the soft robot body [22, 29, 34, 63, 71, 74, 75]. Usually, manipulation system has a rigid body consisting of power source, control system, and other necessary electronics, and a soft robotic arm/manipulator. The speed of process, commercial availability, cost and level of integration are the major benefits of using rigid electronics. However, rigid electronics have limitations to miniaturization, biointegrity, withstanding extreme mechanisms including stretching, twisting, and compressing.

2.5. Materials

Materials of soft robotic systems were mostly found to be the silicone or rubber because of the fact that the soft robotic system should perform flexible motion [19–22, 29, 30, 39, 62, 65]. However, soft robotic systems such as a multigait soft robot utilized elastomeric polymers in order to attain more flexibility [26]. SMA was also widely used materials for soft robotic systems. Since a conventional electrical motor cannot be directly used in soft robots, SMA is chosen to be actuators [20–22].

2.6. Fabrication and system

The enhancement of fabrication technologies of soft material, such as shape deposition manufacturing (SDM), smart composite microstructure (SCM), and 3D printing technology, has a close relationship with the growth of research activities related with soft robots. This is because the fabrication method for manufacturing rigid robot system is not appropriate for the fabrication of soft material and therefore the fabrication technology for soft material is highly demanded.

SDM manufacturing technology, which was developed for rapid-prototyping of rigid material [76], was first used for developing force sensing robotic finger [77]. The advantage of this technology is that it could print both rigid and soft materials to fabricate an integrated part. Thus, SDM has been widely used for developing soft robotic system [78–80]. Similarly, some researchers used a custom designed mold to fabricate their systems [81]. The SCM manufacturing process is also a well-used type of soft robot fabrication technique. SCM enables the fabrication of mesoscale gears and links to be directly used in mesoscale system whereas traditional parts cannot due to large friction. Based on SCM, polymer films and reinforced prepregs can be integrated layer by layer. Thus, soft gear and link structure can be fabricated in mesoscale. Several systems have been manufactured based on this process [82–84]. 3D printing technology has also brought many advantages to fabricating soft robot system since any 3D model can be printed. Therefore, it has become relatively easy to fabricate soft-robot-related parts. Accordingly, production costs and time have been reduced compared with traditional fabrication methods. GoQBot is an example of 3D printed soft robot system [21]. Based on 3D printing technology, ABS plastic molds can be constructed and using this plastic mold, silicone rubber can be made into the desired shape. There is also a soft robot system in which the body was entirely fabricated using 3D printing technology [85].

Traditional robotic systems involve complex calculations and constant analysis of the system, and the environment limits tasks to repetitive and non-versatile functions reliable only in pre-defined conditions. There is a growing need for more versatile and reliable robotic systems which can adapt to uncertain and/or versatile conditions and perform required tasks. In this section, how soft robot systems differ from the rigid robot system and analysis of current soft robot systems are discussed.

There are essentially two types of systems for soft robots in control mechanism: continuum robots with inverse kinetic algorithms and with neural network algorithms [86]. Caterpillar-like soft robot is controlled by internal compressive force through inverse kinematics and dynamics [87]. Many of the soft robots developed are continuum robots which include modeling of the system by piecewise-constant-curvature approximation (PCCA) [21, 88–90]. Another continuum manipulator control systems include steady-state model inspired by the octopus arm and its speed was faster than conventional PCCA [91].

Soft robotic systems overcome the limitations of rigid robots, such as limited degree of freedom and need for complex calculations, through embodied intelligence and morphological computation [92, 93]. Embodied intelligence highlights the interaction of morphological structure and environment to shape adaptive behavior and these results in the adaptability and robustness seen in living organisms. This control concept, which usually involves neural network, could be quite different from the current control mechanisms for conventional robots, estimating unknown model dynamics as it does not involve complex analytical calculations. Neural network is typically trained using the backpropagation algorithm [94].

Soft robotic octopus arm mimicked the adaptability of octopus' morphology, soft and compliant skin with longitudinal and transverse muscular structures, to the environment achieving variable stiffness and good dexterity [92]. A feed-forward neural network learning of soft cable-driven manipulator to perform grasping of various objects proved its feasibility of conventional inverse dynamic calculation methods [86, 95, 96]. PhysX utilizes spiking neural networks to perform gait motion [97].

2.7. Applications

Soft robots have a wide variety of applications ranging from industrial to medical usages. In this section, we will introduce soft robots developed upto date according to their potential application areas; human-machine interface and interaction, locomotion and exploration, manipulation, medical and surgical applications, rehabilitation, and wearable robots.

2.7.1 Human-machine interface and interaction

Soft robots are essentially more compatible for human interactions as their soft and easily deformable bodies ensure a minimal damage and load given to the human and environment [98]. Soft robot's ability to adapt to curved and irregular surfaces allows overcoming the shortcomings of rigid robots. A robotic system much like the biological system in terms of material and mechanics allows better human-machine interaction in almost all areas including but not limited to medical, healthcare, packaging, etc. Human-machine interface is important especially for the medical robots since communication of accurate and real-time data is essential for safe and robust response. Data can be communicated in largely three ways; by wire [30, 36, 37, 39, 63, 64], wireless [66, 74] and independent controller with determined action algorithm or self-decision making algorithm [20, 25, 31, 32, 99]. Most studies require human interventions to perform complex tasks and few simple tasks are self-determined.

2.7.2 Locomotion and exploration

Soft robots are capable of performing locomotions that cannot be seen in rigid robots and thus are able to navigate and explore unknown terrains. They are also able to more efficiently and more robustly move in environments where rigid robots have difficulties such as underwater. Studies of caterpillar-like and underwater creatures have inspired many soft robotic systems in control and actuation methods. They perform rolling, jumping, and crawling motion. GoQBot simulates caterpillar movement and rolls for locomotion [21]. A highly deformable 3D printed soft robot can inch and crawl like a catepillar and can generate dynamically-shape-dependent frictional force differentiated from conventional rigid robots [85]. Inchworm-inspired soft robot composed of smart soft composite perform locotion via abdominal contraction [100]. Meshworm involves peristaltic locomotion similar to that of an earthworm and the use of flexible mesh materials allows external shock absorption [20]. Self-contained serpentine soft robot actuated by FEAs can synthesize snake-like motion with wheels at the current stage [29]. Another animal-inspired soft robot is the multigait soft robot which produces complex gait motion with relatively simple actuation [26]. A more advanced version of this robot is untethered quadrupedal soft robot and it is capable of exploring indoor and harsh conditions outdoor environments with the goal of surveilance [25].

Many underwater animals have also inspired many soft robots to move robustly and in a controlled manner in water. The soft robotic fish has a rigid head with conventional electronics housed within and a soft-bodied tail to perform diving, turning and swimming motion like fish [40]. The octopus soft robot mimics the movement of octopus through utilizing eight legs and has the ability to travel through small apertures and unstructured surfaces as well as perform grasping using its leg [101, 102]. The shell-like soft robot inspired by cephalopds propells itself underwater by dynamic activity of its shell [103].

There are non-animal inspired soft robots. A circular deformable soft robot can crawl and jump to move in a rough terrain [104]. Untethered robots perform jumping by pneumatic and explosive actuators [32, 105]. 3D printed soft robot powered by combustion with on board electronics [106].

2.7.3 Manipulation

Rigid robots have a natural limitation to the types of manipulation they can perform due to low DOF, complexity, and difficulty in calculation of grasping action. Soft robotic manipulators are more compliant and can manipulate fragile and unknown objects by a simple control algorithm having advantage over rigid robots [2]. Soft robot manipulators engage in either granular or octopus-like manipulation methods. A tentacle-like manipulator with embedded pneumatic networks allows grasping of variety of materials, and other functionalities can be added such as needle and visual system [107]. OctArm can grasp objects with varying size, shape, and payload under dynamic disturbances [34]. Many other manipulators are inspired by octopus or other cephalopod limbs [18, 108]. A multisegment soft manipulator with real time positional feedback system have autonomous grasp-and-place ability [109].

2.7.4 Medical and surgical applications

Soft robots inherently have advantage of being compliant with the natural tissues of human and living organisms. Minimally invasive surgery (MIS) is one of the research areas with big potential of adopting soft robotics. This is because it overcomes limitation of traditional MIS methods such as low DOFs [110]. A controllable-stiffness in combination with granular jamming system can be utilized in laparoscopic surgery and endoscopy [111]. Stiff flop surgical manipulator capable of modifying its mechanical properties as needed and stiffness-controllable end-effectors for minimizing damage to surrounding soft tissues and increases accessibility *in vivo* [75, 112]. A cucumber tendril-inspired tactile sensor sleeve for soft manipulators for use in MIS can be used to overcome limitation in lack of haptic feedback in MIS [113]. A soft endoscopic system inspired by elephant's trunk is developed for cardiac ablation in MIS allowing access via confined space and manipulation [114].

2.7.5 Rehabilitation and wearable robots

Biocompatibility and biointegrity are vital criteria for wearable and human assistant applications and these are the main advantages of soft robot over conventional rigid robot systems. Since soft robots utilize elastic and soft material, they exhibit mechanical properties similar to that of living organisms and therefore, are compliant to be used in wearable devices supporting functions of humans and perhaps other animals [98]. Use of soft and elastic materials absorbs mechanical stress and minimizes the chance of injury to both the robot itself and the user.

Soft robotic gloves includes soft actuators for use in hand rehabilitation for patients with grasp pathologies [41]. Similarly, there exists a soft robotic glove for thumb rehabilitation [115]. Another soft robotic glove for hand rehabilitation with human-machine interaction (with clinician) performs specific tasks for training [116]. There are many other works on hand rehabilitation by soft exoskeleton systems [117, 118].

Other wearable soft robotic devices exist for rehabilitation and other applications. The gait rehabilitation soft robot for spinalized rodents uses soft pneumatic actuators in conjunction with rigid frames and their inherent softness is suitable for interacting with soft tissues [119]. Another gait assisting soft robotic exosuit exists for humans, and it can be worn like normal clothing, is light and minimizes unintentional interference with the wearer [120]. The ankle-foot rehabilitation wearable robotic device utilizes pneumatic artificial muscle actuators and mimic muscle-tendon ligament morphology and function [121]. There are many stretchable sensors; a tremor neurobot is a form of sleeve which assesses and attenuates pathological tremors and can satisfy aesthetic appearance preferred by the patients [122]. There is a soft oral rehabilitation robot for people with mandibular mobility disorders [123].

3. DISCUSSIONS

In terms of actuation, three major types, variable length tendon, fluidic actuation, and EAP, have been used. Especially, pneumatic pressure based fluidic actuation has been frequently applied to wide application including locomotion, gripping, and rehabilitation. Major advantages of each actuation approach have been discussed. Sensing is an important function for proprioception of soft robots. For the least effect on the impedance of robot hardware, sensors with low modulus are recommended. Multiple-layered elastomer filled with liquid conductor and IPMC have been frequently reported by the previous researchers. As for the structure of the soft robotic systems, they have been mostly inspired by biomimetics, which is actually the former stage of soft robotics. However, researchers started to use some entirely new approaches and new materials to develop soft robotic systems since the biomimetics also suffers from several limitations. Soft robotic systems require less complex calculations and therefore can perform more versatile tasks than rigid robots such as packaging various goods in industries. Due to the absence or lack of hard components and their flexible nature, soft robots are distinguishably more compatible with biological materials and humans. These appealing properties of soft robots create new opportunity areas where conventional robots have come to limit like exploration, manipulation, medical, rehabilitation, and wearable fields. A hybrid system much like many living creatures would be the most promising system comprising benefits of both.

Soft robots will offer unique properties and therefore opportunities which are previously unexplored. Recently, there is a growing need for devices which can interact with human such as smart watches and unmanned vehicles. Soft robots are suited for interaction with humans due to their soft and compliant nature and their ability to perform works with uncertainties. They minimize damage to the user and the environment via shock-absorbability and are more compatible and reliable with uses regarding biological materials owing to their flexibility. User-friendly mechanical properties of soft robots are the results of advances in new flexible materials and electronics.

4. CONCLUDING REMARKS

Soft robot is a rapidly growing area in robotics as drawbacks of conventional robots such as human-machine interaction and adaptability are alleviated. Also, robots have been evolved from performing labor-intensive, repetitive, and simple tasks to more interactive, dexterous, and high-level tasks. The demands for robots which interact with humans in the areas of military, medicine, rehabilitation, assistive technology, etc. will continue to grow and soft robots could possibly answer these demands. Future soft robots with embedded artificial intelligence could be developed into self-contained navigating (surveillance of difficult to reach areas, rescue mission in disaster zones, etc.) and manipulating (packaging and organization of goods) systems which bring industrial, medical and military benefits. Soft robots are usually inspired by the living creatures and mimic their muscular (actuation), skin (barrier) and, observatory organs (sensors) which are acknowledged more efficient and robust movements. This gives soft robots many benefits compared to conventional robots such as ability to compensate uncertainties in the environments and safe interaction with humans and living organisms. Many animals are vertebrates or insects having rigid structural frameworks along with soft materials, so a mixture of soft robots with conventional robots will be essential to maximize its benefits to achieve the best solution.

This review paper has covered a wide range of soft robots being developed over the past few decades and would benefit soft robot research community by providing overview with some details and up-to-date information. Also, detailed information on the research trends as well as advantages and drawbacks of each soft robot can be found in this review paper.

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