Flexible Actuators for Soft Robotics

Ying Yang, Yanxiao Wu, Cheng Li, Xiaoming Yang,* and Wei Chen*

Rigid robots have taken on a variety of automated manufacturing tasks and have made a huge contribution to industrial development; however, they are not suitable for further wearable applications due to their rigid and bulky structure, poor environmental adaptability, and low safety. Soft robots, which are mainly fabricated with flexible or elastomeric materials, can easily adjust to environmental changes and accomplish complex tasks, offering a new paradigm to achieve human-machine compliance. Soft robots do not replace rigid robots but add diverse features for softer robotic applications. In particular, the use of flexible actuators in robotic systems can realize certain intelligent functions, enrich soft robotic systems and migrate academic research to engineering applications. Currently, the application of flexible actuators in soft robotic fields is still at the embryonic stage. However, tremendous application spaces can be envisaged when combining flexible actuators with soft wearable robotics. Therefore, the current flexible actuators that rely on different external stimuli are addressed herein, and their materials, designs, and approaches suitable for soft robotic applications are highlighted. The application advancement and future perspective of flexible actuator prototypes toward various soft robotics are also discussed.

1. Introduction

Since the development of the Unimate robot by Devol and Engelberger in 1959, rigid robots have taken on a variety of automated manufacturing tasks and have made an enormous contribution to industrial development.^[1] The current robotic systems are interacting more closely with humans.^[2] However, with the recent rapid development of intelligent wearable fields, such

rigid robots have been recognized as unsuitable for more delicate application requirements due to their rigid and bulky structure, poor environmental adaptability, and low safety.^[1-3] As a result, soft robots that are mainly fabricated with flexible or elastomeric materials have emerged^[2-5] and can easily adjust to environmental changes, accomplish complex tasks,^[3] and achieve human-machine compliance.^[2] In particular, flexible actuators offer an important actuation capability^[1] and open up new possibilities for soft wearable applications, such as acting as intelligent surgical or drug delivery tools,^[6–8] powering limb rehabilitation and assistance.^[9-12] smart designing for actively deformable apparel,^[13,14] and establishing soft humanmachine interactions (HMIs).^[13,15] These devices are undoubtedly an integral part of the broad field of soft robotics.^[16,17] Soft robotics based on flexible actuators will not replace traditional rigid robots but will add diverse features for softer robotic applications.^[18-21]

Flexible actuators are a type of device that respond to an external stimulation from the environment and produce a reversible shape change, size change, or property change. Increasingly, researchers and engineers are committing to the development of flexible actuating technology and the integration of soft robotic systems. With the development of flexible functional materials, various flexible actuator designs suitable for human or nonhuman soft robotic applications have appeared. According to

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different stimuli, these devices can be roughly classified into groups, such as electrical actuators, humidity actuators, thermal actuators, and optical actuators. For soft robotic systems on humans, different kinds of actuators are considered to have broad application potentials due to their outstanding characteristics. Among these actuators, ionic actuators are the most promising wearable robotic candidates for electroactive polymers (EAPs), which can directly obtain mechanical energy from electrical energy and have the ability to generate a large deformation at a low-driven voltage, maintain air working stability, and possess a high energy conversion efficiency.^[22–24] The electrodes of ionic actuators have a porous network, a large specific surface area (SSA), and high electrical conductivity, which achieve a sizable ion storage to then present a superior electrochemicalmechanical performance.^[25-27] Various ionic actuators based on the aforementioned mechanism have emerged, greatly promoting the development of soft robotics on humans.^[28-36] In contrast, inspired by hydromorphic organisms, humidity actuators are attractive as flexible actuators for the capabilities of responding to a change in ambient moisture and converting to motion or mechanical work with a superior sustainability and low-power consumption.^[37–39] Synthetic polymers and biological materials have been used to achieve similar hygroscopic actuations, which can be used for soft robotic locomotion on humans.^[40-42] In addition, thermal actuators have emerged as an important branch of flexible actuators. Depending on the different mechanisms of external thermal stimulation, photothermal actuators^[43,44] and electrothermal actuators are the most widely studied because they enable rapid on-off switching, a large force generation at a low actuating voltage, or the control-lable actuation of light.^[43,45,46] Broad application prospects have been shown in the field of soft robotics on humans. Moreover, optical actuators, with the ability of converting optical energy into mechanical energy, offer considerable advantages, including a nonelectromagnetic disturbance, abundant light source, wireless actuating, and remote control.^[47,48] The energy conversion route is a crucial factor in the design of optical actuators.^[25] Hitherto, researchers have studied several energy conversion routes, such as photochemical actuation,^[49] photothermal actuation,^[50,51] photoelectrical actuation.^[52] and radiation-pressure actuation.^[53,54] These studies have laid an important foundation for the application of optical actuators in the intelligent soft robotic field. Moreover, scientists have combined the unique features of the aforementioned types of the stimulations (e.g., light, humidity, and electricity) and designed multistimuli-responsive flexible actuators, further enhancing the performance and enriching the application range of flexible actuators on humans.^[55–57] For soft robotic systems on nonhumans, electrical actuators and pneumatic actuators have been widely investigated by researchers. The materials of electronic actuators mainly include dielectric elastomers, piezoelectric polymers, ferroelectric polymers, and liquid crystal elastomers (LCEs). The systems are actuated by an electric field and static electricity and possess a fast response speed and large actuating stress; however, the devices require an excitation voltage of several kilovolts, and it is difficult to obtain a high stress and large deformation output at the same time.^[58,59] In contrast, pneumatic actuators have been widely investigated due to their simple structure, flexible motion, and excellent adaptability. Robots with bioinspired and rapid actuation have been



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developed and serve as a feasible solution to the development of soft robotics on nonhumans, such as deployable crawlers and swimmers with complex body motions and robust jumpers.^[60,61] These flexible actuating technologies will contribute to the breakthrough of developments in the field of soft robotics.

To date, numerous comprehensive reviews that focused on flexible actuators have been published. However, an exhaustive review of flexible actuators for soft robotic systems remains absent. Soft robotics is a rapidly emerging field that combines robotic and wearable technologies. Currently, the flexible actuating technology used in soft robotic applications remains at the embryonic stage. However, tremendous application spaces can be envisaged when combining flexible actuators with soft robotics. These devices can realize certain intelligent functions,



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Figure 1. Typical flexible actuators, advanced processing and integration methods, and soft robotic applications.

enrich soft robotic systems, and migrate academic research to engineering applications. The soft material properties of actuators provide the special advantages of minimizing restrictions to the wearer and having a minute inertia. For instance, these actuators can be used for assisting with people's healthcare, acting as smart surgical and drug delivery tools, establishing human–machine interfaces, and smart fashion designing for actively deformable apparels. However, new compliance challenges for efficiency and the control of flexible actuators need to be overcome.^[18] Here, we will summarize the flexible actuator research by us and other groups, mainly considering different external stimuli and highlighting materials, designs, and approaches suitable for soft robotic applications. The application advancement and future perspectives of flexible actuator prototypes for various soft robotics will also be discussed (**Figure 1**).

2. Actuation Mechanisms

Actuators, as a class of transducers with mechanical output capabilities, are classified according to different stimuli, such as heat, direct current (DC) voltage, and light signals. When referring to soft robotics, flexible actuators are regarded as a type of intelligent device that exerts mechanical deformation or substance release when being stimulated.^[62]

The term "conventional flexible actuator" is typically used to refer to pneumatic artificial muscles, which are primarily used in rehabilitation devices. However, the large volume of these devices makes for poor wearability. Thus, this technology is better suited for mechanical devices and therefore will not be included in this Review. This section summarizes various actuating mechanisms and the corresponding wearable actuators. Among flexible actuators, electrical actuators have been investigated the most, due to their superior controllability and higher energy conversion efficiency. However, a high voltage (up to 1 kV) or high stimulation temperature is needed for the actuation of inorganic materials. Thus, EAPs seem to be optimal materials for electrical actuators, as they are inherently lightweight, highly flexible, and have a high fracture tolerance.

The deformation of EAPs by electrical stimulation can be divided into either "electronic" or "ionic" categories based on the stimulation mechanism. The electronic EAPs are actuated by the Coulomb force or an electric field. However, for ionic EAPs, the actuation is due to the transport or diffusion of ions.

2.1.1. Electron-Based Actuation (Electronic EAPs)

The investigated electronic EAPs, whose actuation is driven by the Coulomb force or an electric field, show a large strain, rapid response, high mechanical energy output, and the ability to maintain an induced displacement upon interacting with an electrical stimulus. Typical film materials include rubbers, silicones, acrylic elastomers, polyurethanes, fluoroelastomers, polybutadienes, ethylene–propylene rubbers, and polyisoprenes, with various performance characteristics.^[63–65] For dielectric elastomers, the deformation response is induced by an electric field. The electrostatic attraction between soft electrodes generates the actuation (**Figure 2**).^[66]

When assembled with different types of electrodes, dielectric elastomers can produce a large strain between 10% and 100%; however, when applying a high electric field, the strain can reach up to $380\%^{[67]}$ and can export stresses as high as 7.7 and 3.2 MPa for silicone- and acrylic-based actuators, respectively. Such large strains allow these devices to produce high work densities of up to 3.4 MJ m^{-3} . Silicone- and polyurethane-based elastomers exhibit the benefits of softness and rapid response and are



Figure 2. Illustrations of the different actuation mechanisms for a dielectric elastomer. a) Coulombic interactions between oppositely charged soft electrodes generating a Maxwell stress. b) Direct coupling between the polarization and electromechanical strain response generating a true electric field. Reproduced under the terms of the CC-BY 3.0 License.^[66] Copyright 2012, The Authors. Published by InTechOpen.

castable in any shape. However, their mechanical strain is considerably low. Silicones have a low dielectric constant (ϵ), resulting in the need for an increased stimulating voltage compared with that for acrylic elastomers and polyurethanes.^[68–70] However, a disadvantage of dielectric elastomer actuators is the high-driven voltage (1–10 000 V), which may be unsafe for applications surrounding the human body, such as textiles. In addition, the need to convert stimulated voltages of up to kilovolts further makes these actuators unsuitable for human applications, as these higher voltages would add cost and volume to the devices.

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Ferroelectric polymers are another kind of well-investigated electronic EAPs and represent a kind of crystalline polymer that can change from a polar to nonpolar state, thus, generating lattice strain and deformation via electric fields.^[71] The optimal choice of polymer has been the piezoelectric material poly(vinylidene fluoride) (PVDF), as well as its copolymers and terpolymers.^[72] Huang et al. reported an actuator of PVDF with a strain to 7% at $\approx 150 \text{ MV m}^{-1}$.^[73] Bauer et al. showed a ferroelectric nanocomposite with a high electrostrictive strain (>7%) and elastic modulus (>0.3 GPa).^[74] PVDF and its copolymers present a weak strain compared with that of dielectric elastomers; however, the responding stress is tremendous, as high as 50 MPa, compared with the several MPa of dielectric elastomer actuators. However, the huge molecular strain caused by a configuration change results in a large strain hysteresis. Similar to dielectric elastomer-based devices, the stimulation voltage of PVDF is too high for soft wearable applications. Another main shortcoming of ferroelectric polymers is the huge hysteresis involved.

2.1.2. Ion-Based Actuation (Ionic EAPs)

Although electronic EAPs usually show a high mechanical output and actuation force, their main shortcoming is the high stimulation voltage needed, which is not suitable for wearability. Comparatively, although electrolytes with mobile ions are needed, ionic EAPs, which are able to be stimulated at a low voltage (from one to several volts), have been well investigated for their potential use in wearable applications, with ionic polymer–metal composites (IPMCs), soft gels, and conducting polymers (CPs) usually investigated.

Ionic Polymer–Metal Composites: A classic IPMC actuator layout involves two thin flexible electrodes (typically Pt and Au) with an ion-conducting polyelectrolyte between them, allowing for the application of an electric field across the film.^[75,76] Hydration allows positively charged ions in the film to move freely, whereas negatively charged ions bond with the carbon main chains of the polymer and thus, are fixed. Electric fields cause the positively charged ions to aggregate near the cathode, exerting a stress gradient on the aggregation of molecules due to their high concentration. This strong localized stress causes bending and is thus the actuation source of the IPMC structure.

The water content of IPMCs means that they must work under water or in a moist environment. Unfortunately, this is not suitable for the development of soft wearable devices in air. To increase their working ability in natural environments, IPMC actuators without water have been developed. These devices contain air-stable ionic liquids (ILs), instead of hydrated moving ions.^[77–80] As is known, these ILs possess a low volatility, a wide working potential window, and high ionic conductivity, which allow for the stable and rapid response of devices. Chen and coworkers developed different types of actuators, based on different materials, with a fast response and large strain at low voltages, as shown in **Figure 3**.^[25,81]

Conducting Polymers: The actuation mechanism for CPs has been extensively studied in many reports.^[67,77] CP-based actuators utilize the mechanism of deformation of the polymers, which is due to charge removal from or addition to the main chain. When the oxidation state of CPs change, their dimensional change is large. Thus, these CPs can convert electrical energy into mechanical work. Conductive conjugated-polymer actuators are lightweight, flexible, and biocompatible and can be operated at low voltages. Their low self-discharge performance, lack of mechanical creep, super force-generation ability, and excellent energy density are highly advantageous.^[82]

The most common materials incorporated in CP-based actuators are polypyrrole (PPy), polyaniline (PANi), and poly(3,4-ethylenedioxythiophene)/poly(styrene sulfonate) (PEDOT/PSS). Due to the rigid structure of these polymers, they are stable compared with other linear CPs.^[83] PPy is the most investigated material for actuators. The electrochemical changes in the oxidation state of PPy result in the ingress and egress of charge to and from the polymer main chain. Due to the charge imbalance, there is a flow of ions to balance the charge. This flow of ions, which may be accompanied by solvent (as in IPMCs), causes the contraction or swelling of the polymer. Predominantly, the facile electrodeposition of PPy generally makes it possible to obtain films of high conductivity and toughness, providing a high strain, mechanical output and long cycle life.^[84,85] Alternatively, PANi can be synthesized by oxidative polymerization in aqueous solutions, resulting in a low strain of actuators when compared with that of PPy.^[86,87] Another material PEDOT/PSS has been investigated as a conductive coating in soft wearable devices.^[88-90]

The electrochemical potential (1–2 V) required to initiate the actuation results in a mechanical strain ranging from 1% to 40%. CP actuators have exhibited both linear movement and bending. These devices possess a high mechanical performance of up to 100 MPa.^[82] Furthermore, CP-based actuators can bear a large stress of 34 MPa.^[91] The strains of these devices are usually 2%–7%, and the enhancement for investigated CP-based actuators has been as high as 20%. Compared with IPMCs, CP actuators show a high output force but a slow response. This behavior is due to the diffusion of ions, which move in and out of the main chains, and the internal resistance between the CP and electrolyte solution. The ability of conducting conjugated-polymer actuators to produce linear strain^[92] was used by Must et al. to investigate the structure and performance of ionic EAP-based actuators,^[93] such as in sandwich structure benders,^[94] cantilevers,^[95] and rolling^[96] and walking robots.^[97]

An operational barrier for many linear CP actuators is the presence of the electrolyte. Other disadvantages include their high sensitivity to oxygen, limited cycle rate, and limited cycle life.

Carbon-Material-Based Actuators: Carbon nanotubes (CNTs) are allotropes of carbon and exhibit novel properties, such as extraordinary strength and high electrical and thermal

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Figure 3. a,b) Schematic of the construction of and mechanism behind a graphic carbon nitride electrode-based soft actuator. Reproduced under the terms of the CC-BY 4.0 License.^[25] Copyright 2015, Springer Nature. c,d) An illustration of the actuation mechanism of a graphdiyne actuator. Reproduced under the terms of the CC-BY 4.0 License.^[81] Copyright 2018, Springer Nature.

conductivities, suggesting their potential for use in many applications.^[98] Given the poor stretchability of CNTs, they should be made into films, known as buckypaper^[99] or yarns.^[100] CNTbased actuators were first demonstrated by Baughman and coworkers.^[82,101] However, the produced strain remained at 0.7% and 0.5% for single-walled nanotube (SWNT), and multi-walled nanotube (MWNT) yarns, respectively, which have relatively low values compared with that of other actuators.^[102] A comprehensive review on CNT actuators and sensors was published by Li et al.^[103]

Electrostatics and double-layer charge injection can be used to electrically actuate CNTs.^[103,104] The latter is an electrochemical reaction, in which various ions are injected into the surface of the carbon nanomaterial. An applied DC electric field causes the movement of electrons from the liquid to the carbon surface, resulting in a positively charged liquid and negatively charged nanocarbon structure. As the distance of the covalent bonds increases, as well as the separation between two carbon layers changes, the total carbon material expands or contracts.

CNT torsional actuators have also been realized using twistspun yarns.^[105,106] The actuation mechanism for CNT actuators was investigated and explained by Foroughi et al. with twisted torsional artificial muscles.^[107]

Recently, our group reported on molecular-scale active graph diyne-based electrochemical actuation with an electrome-chanical transduction efficiency as high as 6.03% and an energy density as high as 11.5 kJ m⁻³, exceeding those of reported materials.^[81] *Gel Actuators*: Gels are another kind of well-studied actuator material, and a solvent is usually essential for gels. However, polyvinyl chloride (PVC) gels with a plasticizer can function without a solvent supply, allowing them to operate in air. The actuation of PVC gels between electrodes is usually at the millimeter scale, as the deformation response results from both ion migration and Maxwell forces in an applied electric field (**Figure 4**). A moderate stimulated voltage (1–10 000 V) is required by PVC gels, which is considerably lower than that of electronic EAP actuators. However, the system remains unsafe for application in wearable devices. In addition, the elastic modulus of PVC gels is no more than 1 MPa, which tends to be too soft, making for a very small output force (\approx mN).

2.2. Humidity Actuators

Most botanical movements are hydraulic in nature, that is, the simple transport of water in and out of the plant tissue generates motion. In particular, the hygroexpansive properties of plant cells, leading to a volumetric change in response to moisture content, are exploited by many plants for activities, such as the opening and closing of pinecones, the self-digging of wild wheat seeds, and the opening of seed pods and ice plant capsules. Inspired by nature, humidity-based actuators can be fabricated to convert actuation from water or moisture into a size change, making for an efficient use of the environment. The ease of access to water, and its safety, distinguish this form of actuation

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Figure 4. Schematic of PVC gel deformation. Reproduced with permission.^[108] Copyright 2009, Elsevier.

from other potential response systems. The mechanism of humidity actuation is attributed to the in-and-out migration of water molecules. In pioneering works, many efforts have been made to fabricate humidity-responsive actuators based on various materials, including cellulose nanofiber,[109,110] PPy,[40] graphene,^[111] polydopamine,^[112] and so on. Recently, Arazoe et al.^[39] reported a sensitive film actuator driven by fluctuations in ambient humidity using a carbon nitride polymer. This actuator exhibits a relatively small bending stiffness; however, the sensitivity to water vapor is not sufficient for fast actuation, and the actuator cannot bend in the desired direction. Alginate is a renewable natural polysaccharide with excellent biological stability and good environmental safety. Alginate forms a hydrogel structure by quickly swelling in aqueous solutions with divalent cations. When removing the water from the gel, the alginate gel fiber can transform from the wet state, with a smooth surface, to the stable torsional state, with a rough and wrinkled surface. These characteristics impart alginate fiber with a good water adsorption and desorption performance and moisture actuation.^[113] Hygroscopicity also results in the giant volume change of silk upon moisture absorption,^[114] indicating that silk would also be an optimal candidate for twist-based actuators. More research on traditional humidity-responsive robotics was conducted in the work of Ma et al., where an inchworm made of PPy, on the millimeter scale, was developed.^[40] The inchworm is driven by water gradients and can generate mechanical stresses as high as 27 MPa, allowing it to lift cargo 380 times than its own weight.^[115] Another example from Ma et al. demonstrated a polyelectrolyte multilayer film actuator that uses periodic changes in relative humidity between 11% and 40% for actuation, allowing it to carry and move loads of up to 120 times its own mass.^[116] Actuators based on liquid crystals (LCs) that respond to humidity were reported by Dai et al., and the devices show the bending of the bilayer structure.^[117] In the next year,

Chen et al. demonstrated deformations such as folding, bending, and twisting with a LC polymer sheet.^[118] Recently, our group reported an actuator driven by the moisture gradients of a homogeneous graphene oxide (GO) film, due to the in situ formation of a bilayer structure caused by water adsorption (**Figure 5**). This actuator displays fast and controllable bending motions, along with the ability to lift objects eight times heavier than its own weight.^[119] Because the materials are largely abundant and cost effective, humidity actuators will open the path to more abilities in smart textiles and soft robotics.

Moisture-based textiles that can adjust their porosity, adapting to environmental perspiration, humidity, rain, and temperature, are of great interest. They can provide increased comfort for human beings through humidity and thermal management.^[120] The rapid response speed, high sensitivity, and excellent cycle performance of artificial moisture-responsive materials highlight their potential as smart materials for applications in soft wearable robotics. However, large challenges remain in this field, including the capability to simultaneously achieve quick, sensitive, and durable reconfigurations stimulated by moisture, which will be a key problem to solve. Other sources, such as thermal, optical, magnetic, pressure, and chemical, are not easily available, compared with electric sources and moisture sources, and consequently, the integration of these stimuli into soft wearable devices is not simple.

2.3. Thermally Driven Actuators

When applying heat to a film actuator, it will contract, elongate, or bend due to the phase transition or molecular isomerization of soft materials. The stimulus can be applied via several approaches, such as through electrothermal effect, thermal radiation, and the laser-induced thermal effect.



Figure 5. Mechanism for the locomotion of the homogeneous thin-film GO actuator. Reproduced with permission.^[119] Copyright 2018, the Royal Society of Chemistry.

2.3.1. Phase-Change-Directed Actuator

Electrothermally driven CNT actuators have been investigated to overcome the presence of electrolytes for actuation. The electrothermal drive of CNTs is gained by a combination with other materials that can contract and expand thermally, such as paraffin wax^[121] and silicone polymer elastomers.^[122] Generally, the volume change in the matrix polymer initiates the electrothermal actuation mechanism of the fibers of combined CNTs. Nevertheless, devices built using electrothermally driven CNT composites need a high-driven voltage compared with that of other devices.^[87]

One of the most investigated polymer materials is poly(*N*-isopropylacrylamide) (PNIPAM) due to its suitable performance at room temperature.^[123] The work of Stoychev et al. showed that a bilayer of biodegradable hydrophobic polycaprolactone and PNIPAM can encapsulate and release yeast cells.^[124,125]

2.3.2. Shape-Memory Polymers

The shape-memory effect in certain metals and shape-memory alloys, such as nickel titanium, has been commonly applied in soft robotics. However, we will not discuss this topic in depth here since our main interests deal essentially with soft polymers. Shape-memory polymers (SMPs) are materials that can "remember" several conformations. The polymer can deform temporarily, and the deformed configuration can be maintained under given conditions, such as polymer crystallization. This configuration can then by recovered via stimuli.^[126,127] Unlike other flexible actuators, the transition between states is not continuously controllable, as only the states are changing. These transitions can be used to tune the stiffness of the polymer, which presents broad application spaces.^[128,129] Recent SMP reviews include those by Mirvakili et al.,^[130] Schubert et al.,^[131] Li et al.,^[132] Huang et al.,^[133] and Behl et al.^[134]

Amorphous crosslinked polymers display elastic behavior above the glass transition temperature, T_g , whereas crystalline crosslinked polymers display the same elastic behavior above the melting transition temperature, $T_{\rm m}$.^[128] The polymer can be strained easily in the elastic region, and that mechanical strain is stored when the material is quenched below T_g or T_m . Increasing the temperature again releases the stored strain, resulting in return to the original configuration. A demonstration of this thermomechanical cycle is shown in Figure 6. There are various types of reversible SMPs that are currently being studied. However, SMP-based actuators are one-directional actuators whereby manual deformation is needed to reset the material, which restricts their application. Reversible bidirectional SMPs, in which an external stress is not required, have recently been reported,^[135,136] but they are not common. Some reports have used LC materials with a repeatable phase shift to generate a reversible shape-memory effect.[131]

Conductive fillers, such as CNTs, carbon black, and PPy, can be used to improve the electrical and thermal conductivities of an actuator. Furthermore, these fillers can also improve the actuators' recovery stress and mechanical strength.^[138–144] For example, an SMP with these conductive fillers can be strained up to 1000% and recovered to 400% strain before failure.^[145] Voit et al. improved these results and achieved a fully recoverable strain of over 800% at a glass transition temperature of only 28 °C.^[146] A comparison of several SMPs with strains approaching 200% indicated that the elastic energy density is between 0.01 and 2 MJ m⁻³. The best material was found to exhibit elastic energy density values higher than 1 MJ m^{-3.[147]}

2.3.3. LC Polymers

A stimulus, usually heat, causes LC materials to experience a phase transition from an ordered phase to a disordered phase. The former is an ordered mesogen arrangement, whereas the latter corresponds to a disordered arrangement. The mesogen organization in these materials is used to define the material's phase, primarily between nematic and smectic phases. The nematic phase leads to a uniform orientation of the mesogens, whereas the smectic phase involves separate layers in which the mesogens are organized.^[148] The LC phase is important, as it affects the actuation method and the resulting motion from actuation. Heating an LC material from the nematic phase to an isotropic phase produces a reversible and repeatable contraction, as shown in **Figure 7**.^[148] Wermter et al. showed that the phase transition from nematic to isotropic can result in a gigantic strain of $\approx 300\%$.^[149] Further reviews on LC materials were recently published.^[150]

LCEs are crosslinked LCPs that show a large deformation ability and display a behavior similar to that of rubber, for example, inhomogeneous and anisotropic LCEs were stretched to pattern the mesogen orientation by Ahn et al.^[152] In addition, polarized light and photomasks have also been used to achieve a controlled alignment, allowing for the production of patterned and structured films.^[153,154] Ware et al. demonstrated that a heated strip was able to lift cargo 147 times the mass of itself. In addition, specific and volumetric energy densities of 2.6 J kg⁻¹ and 3.6 kJ m⁻³ were reported, respectively.^[153] The crosslinking structure and the material programming developed via these methods are generally permanent. However, retainable LCE actuators were reported by Pei et al.^[155] Recently, exchangeable covalent links, whose topology can change with the temperature, were used to develop LCEs, which can be heated, allowing for actuation into a new shape.^[155] In addition, LCE pillars below 100 μ m were reported to exhibit contractions of $\approx 400\%$,^[148,156] and LCEs for actuators and sensors were summarized and reviewed by Yang et al.,^[157] Ohm et al.,^[158] and Li and Keller.^[159]

The primary stimuli for thermally triggered actuators include thermal radiation, near-infrared (NIR) or infrared (IR) light, and Joule heating. These types of stimuli are typically safe, as they can be used near living cells-remaining between 4 and 37 °C when temperature is used. However, these actuators tend to be significantly slower and less efficient than actuators based on other stimuli. Thinner films, more heat-absorbent materials, and higher powers are being investigated to improve the efficiency and speed of thermally triggered actuators. The distribution of carbon throughout a material, or a thin film, can allow for electroand photothermally triggered actuations, without hindering the flexibility of material. As such, thermally triggered actuators are more typically used as a composite component, rather than primarily for soft actuation. Similarly, bilayer actuators of an elastomer and carbon nanomaterials, such as GO and CNTs, have also shown large bending strains.[45,47]

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Figure 6. Programming of an SMP: nonreversible and reversible shape-memory effects are shown on the a) macroscale and b) molecular scale. Reproduced with permission.^[137] Copyright 2019, Springer Nature.



Figure 7. The mechanism for the deformation of crosslinked LCPs caused by the phase transition from a LC (order) to an isotropic phase (disorder). Reproduced with permission.^[151] Copyright 2018, the Royal Society of Chemistry and the Chinese Chemical Society.

Thus, when driving the actuator, the temperature rises up to a potential user's body temperature, which makes the actuator not suitable for wearable applications that contact the human skin directly.

2.4. Optical Actuators

Light-induced soft actuation allows for control on the nanoand microscale, remotely and accurately.^[160,161] Photochromic molecules are used in photoresponsive actuation, translating optical signals into useful material changes such as strain.^[162] Examples of induced deformations of materials include contraction, bending, and swelling motions. Changing the wavelength or removing the source of light can be used to reverse these deformations. The actuator response depends on several external factors, including the wavelength, intensity, and irradiation time.^[162]

Photoresponsive LCPs are typically generated by azobenzene functional groups. The addition of an azobenzene filler to the material, followed by irradiation, causes a macroscopic deformation on the microscale. This motion is driven by strain gradients and unequal isomerization patterns induced by light.^[163] Generally, most of these actuators are films, in which light is absorbed in the top layer (thickness: 10 µm).^[164] The azobenzene chromophore absorption of ultraviolet (UV) light results in a significant film contraction of the surface, thus, bending the films.^[162] Iamsaard et al. prepared an actuator cut from a chiral mesogen-aligned film, which allows for the expansion or contraction of helical spring-like motions. These actuators can maintain a steady state for minutes under UV light, and relax in seconds under visible light (**Figure 8**).^[165] van Oosten et al. demonstrated that an internal gradient in the crosslink density can cause the bending reversibility of a cantilever under a constant UV light source.[166]

Cinnamic moieties have been used to develop SMP films that are reversible via the stimulation of light.^[168] Similar to the thermally induced SMPs, photoresponsive SMPs are initially stretched externally and then exposed to UV light to maintain the deformation shape. Upon release of the external force, the elongated configuration is maintained until irradiation of a different wavelength causes the return to the initial configuration.^[169] However, the UV light is harmful to human beings, and other light sources such as infrared light were introduced.

2.5. Other Actuators: Pressure and Magnetic

2.5.1. Pressure: Fluid-Based Soft Actuators

Liquid droplets can be made nonwetting by coating them with hydrophobic particles. Aussillous and Quéré developed such a composite and termed it liquid marbles.^[170] McHale et al. reviewed the active droplets.^[171] In addition, Grzybowski

et al.,^[172] Ooi and Nguyen,^[173] and Bormashenko et al.^[174] reviewed the liquid marbles.

These actuators act as stimuli such as changes in pressure, viscosity, or surface tension on the surface of a liquid. Unfortunately, compared with solid-material actuators, fluid-based actuators have several disadvantages. Leakage limits the repeatability of fluid-based actuators. Small objects may be captured by the fluid, making reliable transport of the materials difficult. Fluid flows undergo complex dynamics and may mix in unexpected ways when dealing with other fluids. In addition, fluids are highly susceptible to certain conditions of the environment and small quantities can evaporate, which prevent their application in flexible actuators.

2.5.2. Magnetically Responsive Wearable Actuators

An external magnetic field can be used to actuate magnetic fillers in a soft composite. Magnetic particles can be incorporated into soft materials, creating a magnetization actuator where the magnitude and magnetization direction can vary. An external magnetic field causes these particles to align with the field and generate torque, deformation, contraction, elongation, or bending. However, this kind of actuator is hardly used in soft wearable applications due to the difficulty in controlling the device.

3. Advanced Processing and Integration Methods

Structuring and integrating materials for flexible actuators are essential to their characterizations and applications. For instance, soft materials have been integrated into patterns that have achieved a high output force and rotational performance. Researchers have followed different fabrication processes and integration methods using a variety of flexible materials. The aforementioned flexible devices are almost all polymers, which means they are adept at shaping and processing. Different preparation processes have attracted a wide range of research interests, such as electrospinning,^[175,176] spray coating,^[177] knitting,^[178,179] weaving,^[179] and solution casting. Lewis first integrated nanomaterials in flexible actuators^[180] and then conducted research on approaches to apply those actuators in wearable robotics. Several typical actuators have been widely investigated, such as film-, strip-, and patch-based actuators, fiber- and yarn-based actuators, and weaving-



Figure 8. Mechanism for LC photoresponsive actuators based on azobenzene photoisomerization. Reproduced under the terms of the CC-BY 4.0 License.^[167] Copyright 2015, Springer Nature.

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knitting-based actuators. Different performances, including a large deformation^[98] and rapid response,^[89] can be combined with the deformation of a material.

3.1. Film-, Strip-, and Patch-Based Actuators

Flexible actuators with a trilayer structure are often synthesized in the form of a membrane or strip, and then, they can be integrated in wearable devices as patch or as membrane actuators directly. For example, a wearable microdepot was prepared by first coating a viscous silicone layer onto a glass slide, and then, Dragon Skin was casted on top of the film. The application of tensile strain to the strip promoted drug release from the microdepot, due to the increased surface area for transport and Poisson's ratio-induced contraction of the microdepot (Figure 9a).^[181] The bending deformation of a perfluorosulfonic acid ionomer film caused by moisture motivated the design of a personal humidity and heat management system, which was developed by Mu et al. $^{[182]}$ A perfluorosulfonic acid ionomer film with patterns able to induce deformation was integrated in a commercial sports shirt and studied to develop clothing for personal humidity and heat management, as shown in Figure 9b. The PVC gel clamped between two electrodes shrinks when an electric field is applied. When the electric field is removed, the gel returns to its former shape. The structure of a contraction type of PVC gel actuator was investigated using mesh-type electrodes.^[183] The PVC gel was clamped between stainless mesh electrodes. The anode was located above the PVC, whereas the cathode was below the PVC. The application of an electric field causes the gel to creep, moving into the holes of the mesh. The stacking of the layers increases displacement, allowing for expansion and contraction to be actuated. The mechanism for the PVC gel actuator is shown in Figure 9c.

3.2. Fiber- and Yarn-Based Actuators

Flexible actuators can be fabricated as fibers or yarns to enhance the mechanical strain output. The fibers and yarns are classified into different categories: monofilaments, multifilaments, single strands, or staple varns. Various types of flexible actuators based on coiled and twisted varns have been investigated and can cause a rapid, large tensile output and a large-angle twist actuation driven by different stimuli, due to volume expansion and contraction.^[184-186] The speciality of using varn-like wearable actuators with the twisted configuration is that the twisting technique is an ancient and well-studied processing technique in the textile industry.^[187,188] Yarns from polyethylene, nylon,^[189] graphene,^[184] and CNTs^[185] have been investigated for use in wearable devices based on the twisting method (Figure 10a). In addition, Spinks et al. demonstrated a continuous fabrication process for CNT yarn.^[190] The CNT yarn were further developed by combining the old method of twisting during the process of spinning. As shown in Figure 10b, the CNT fiber was fabricated from MWNTs, and after twisting, high-strength CNT yarns were fabricated, where the strength of yarn is up to 460 MPa. Furthermore, the twisted CNT yarns show an improved torsional actuation, which provides potential for use in many types of applications. The twisted CNT yarns were implemented for torsional actuation and reveal broad applications for use in muscles.

3.3. Weaving- and Knitting-Based Actuators

There are several natural advantages of textiles, such as wearability, compliance, high surface area, and ubiquity. Textile actuators combine one of human beings' traditional technologies with advanced functional materials. This combination of flexible



Figure 9. a) Pulling-stimulated drug delivery strip developed by Di et al. Reproduced with permission.^[181] Copyright 2015, American Chemical Society. b) Personal humidity and heat management system. A PFSA matrix with half-round patterns that can bend in an outward direction was integrated into a commercial T-shirt to fabricate a textile for personal heat and humidity management. Reproduced with permission.^[182] Copyright 2018, Springer Nature. c) An illustration of the multilayer-type PVC gel actuator. Reproduced with permission.^[183] Copyright 2009, IEEE.





Figure 10. a) Flexible fiber actuators fabricated by nylon 6,6 fibers. Reproduced with permission.^[189] Copyright 2017, American Association for the Advancement of Science. b) An illustration of yarn fabrication for torsional and tensile actuation. Reproduced with permission.^[87] Copyright 2014, American Chemical Society.

actuators with textiles has been investigated in reports mostly using ancient textile fabrication methods.^[178,189] The two main textile fabrication methods are weaving and knitting. The former utilizes two perpendicular and individual yarn systems, warp and weft threads, which come in close contact and result in a soft fabric. The latter involves the threads being kept together by loops that provide a latent potential for being easily deformable. CPs were^[179] successfully fabricated into textile-like yarns and knitted or weaved into the flexible actuators by Maziz et al., as shown in **Figure 11**a. Knitting these yarns

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Figure 11. a) Knitting and weaving textile actuators (textuators). Reproduced with permission.^[179] Copyright 2017, The Authors. Published by American Association for the Advancement of Science. b) The process for producing a knitted CNT/SPX textile. Reproduced with permission.^[178] Copyright 2016, American Chemical Society. c) Four types of knitting patterns (plain, garter, rib, and seed patterns). Reproduced with permission.^[191] Copyright 2017, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. d) A bionic bra fabricated with woven actuators. Reproduced with permission^[192] Copyright 2018, The Authors. Published by SAGE.



together results in a 53 times higher strain than that of the woven yarn-based textile. An integrated knitting processing method was used to prepare an actuated fabric based on a spandex (SPX)/CNT composite thread.^[178] The textile demonstrates a huge tensile contraction (as high as 33%), providing a work density and power output as high as 0.64 kJ kg⁻¹ and 1.28 kW kg⁻¹, respectively, far exceeding those of a mammalian skeletal muscle (Figure 11b). The use of morphing concepts that rely on the yarn and the looping architecture is advantageous. The loop-linked morphing structures can morph in various modes, which can result in bending, twisting, and torsional deformation, as well as volumetric transformation (Figure 11c).^[191] Furthermore, a bionic bra was demonstrated using nylon actuators to minimize breast discomfort during exercise.^[192] Figure 11d shows the wearable actuators that were used to adapt to breast movement.

3.4. Other Processing and Integration Methods

The traditional and advanced processes of spin coating, screen printing, dip coating, and digital ink-jet printing have been regarded in the rapidly developing field of printed devices. The ability to manufacture and integrate flexible actuators into textiles by these methods has been evidenced. For example, Taccola et al.^[193] adopted a processing strategy to prepare flexible actuators that consists of steps including spin coating, direct laser cutting, and patterning. This strategy enables an efficient and facile synthesis to develop flexible actuators with a complex design.

4. Applications of Flexible Actuators in Soft Robotics

Soft wearable robotics offer the opportunity to adorn robots that endow the body with functionalities, utilize fashion to interpret active deformation, and achieve soft HMIs.^[18,194] Due to their multiple inherent advantages, such as lightweight, multiple degrees of freedom, and high adaptability, flexible actuators have emerged as a dynamically evolving research field in the recent years.^[10] Although the flexible actuating technology developed for the soft wearable fields is currently in its infancy, collaborative efforts toward functional materials, actuator devices, and integration approaches will lead to multiple applications for soft wearable robotics. In this section, several typical application scenarios will be introduced, such as medical and rehabilitation robots,^[6,7,10,181,195–198] designs for actively deformable apparel,^[13,14,199–201] and soft HMIs.^[15,60,202–208]

4.1. Medical and Rehabilitation Robots

Recently, people have expressed an increased demand for patient-friendly treatments. Flexible actuators provide new possibilities for medical and rehabilitation applications. Biocompatibility is one of the most important factors to consider in the medical and rehabilitation robotic fields.^[194] Compared with rigid devices, flexible actuators are made of elastic or soft materials, so they are more compatible with human tissues and can greatly reduce the risk of discomfort or injuries. $^{\left[10,11,194,209,210\right] }$

4.1.1. Surgery Robots

Minimally invasive surgery (MIS) has become a trend, due to its faster recovery and unnecessary trauma.^[6] In surgery procedures, the path to the target may be obstructed by organs or other tissues. Rigid or semirigid devices may increase the risk of injuries.^[194,211] Many flexible actuators for soft surgery robots have been developed with the aim to achieve flexibility, accuracy, safety, etc., and these machines will act as surgery manipulators and artificial organs during surgery.

Surgery Manipulators: Flexible actuators have been designed and prepared not only for their desired use in surgical scenarios but also to act as catheters. For instance, Gerboni et al.^[195] developed a modular soft manipulator for MIS that can be wirelessly controlled based on flexible fluidic actuators (Figure 12a). The characterization of the single-module behavior is the first step to achieve future multimodular control. Haghighipanah et al.^[212] developed a cable-driven robot enabled by a compact design, allowing the actuators to be mounted away from the joints. The authors further estimated the initial values for the cable tension, haptic feedback, and external force acting on the robot, which are vital for the diagnosis of healthy tissue and to prevent damaging tissue with excessive force. In addition, IPMC molecular-regulation catheters have been developed due to the advantages of controllable angles and direction changeability, as well as the multiple degrees of freedom at a low actuating voltage (\approx 1.0 V), as shown in Figure 12b.^[213]

Artificial Organs: Artificial organs supporting natural organs have the similar requirements of warranting safe synergistic interactions with humans. In addition, their materials are required to be mechanically coupled and synchronized because they are implanted.^[194,216] Flexible actuators have the ability to mimic the physiological functions of natural organs and maintain the aforementioned characteristics. The heart has been the center of organ research due to its key role in human health. For example. Pavne et al.^[216] presented an implantable robotic system for heart dysfunction. Flexible actuators were wrapped around the ventricle, to achieve synchronous contraction and relaxation with the heart by programming. Inspired by creatures in nature, Roche et al.^[214] developed a soft robotic sleeve to assist cardiac ventriculation, as shown in Figure 12c. To simulate the orientation of the outer muscle layers of the heart, actuators were designed in helical and circumferential modes, whose stiffness value was of the same order of magnitude as that of the heart. The authors also demonstrated the feasibility of the sleeve in a porcine with acute heart failure. In summary, these soft wearable robotic devices have the potential to serve as rapidly deployable systems for mechanical circulatory assistance in heart failure.

4.1.2. Drug Delivery Robots

Furthermore, several therapy processes need the long-term delivery of drugs; therefore, surgical tools are not suitable.^[194] Drug delivery robots enable sustained, active, and controllable drug



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Figure 12. a) Schematic configurations of a soft modular mechatronic manipulator system and the flexible fluidic actuator working principle designed by Gerboni et al. Reproduced under the terms of the CC-BY License.^[195] Copyright 2015, Springer Nature. b) The schematic actuation mechanism, sectional configuration, and various deformation states obtained by applying a voltage to the IPMC catheter developed by Lu et al. Reproduced with permission.^[213] Copyright 2018, the Royal Society of Chemistry. c) A soft robotic sleeve for the heart designed by Roche et al. Reproduced with permission.^[214] Copyright 2017, American Association for the Advancement of Science. d) A soft paretic ankle assistance exosuit developed by Bae et al. Reproduced with permission.^[215] Copyright 2018, the Company of Biologists Ltd. e) A sensorized actuator fitted in a glove to achieve finger rehabilitation monitoring. Reproduced with permission.^[209] Copyright 2016, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

release to be possible. Different from the digestion and metabolism of the drug in the gastrointestinal tract, the pathway of drug delivery helps the patients to reduce or avoid the burden on the gastrointestinal tract.^[8,217] Drug delivery has advanced to dynamically respond to external stimuli.^[217] For instance, Di et al.^[181] presented a drug delivery device triggered by tensile strain, which conveniently achieves a sustainable and controllable drug release by body motion. Mousavi et al.^[218] developed a single reservoir drug delivery chip controlled by IPMC actuators with a low received power of 20 mW. Moreover, Chang et al.^[219] designed a radio frequency-controlled IPMC actuator, which delivers the drug to the aqueous surroundings via wireless activation. These endeavors have shown promising results toward the intended drug delivery application.

4.1.3. Rehabilitation and Assistance Robots for Humans

Rehabilitation and assistance robots for active exercise can empower certain movements for humans.^[220,221] Researchers have conducted extensive research on exoskeletons, orthosis, and exosuits for multiple parts of the body, mainly for lower limbs and hands, which utilize flexible actuators to drive them.



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These devices have the potential to overcome the availability and cost constraints of therapists while meeting safer, more compliant, and more efficient requirements.^[11,210] In contrast, robotic lower-limb exoskeletons and orthoses can significantly improve the walking ability of patients suffering from stroke or spinal cord injuries (SCI).^[11,222] For example, to develop walking rehabilitation and assistance robots with flexibility and portability, Bae et al.^[215] created a wearable robot based on textile, which transfers mechanical power from actuators to the paretic ankle and then cuts the metabolic cost of hemiparetic walking (Figure 12d). In contrast, the increasing therapy requirements of neurologic disorders have given rise to the development of hand rehabilitation and assistance robots, aimed to recover hand function.^[223] They can execute repetitive and accurate exercises and provide highly specific feedback to assist the process.^[224] Flexible actuators are being rapidly developed as active response devices. For example, Yeo et al.^[209] integrated a soft sensorized actuator, consisting of a pneumatic actuator and a strain sensor, that enables the measurement of the extent of actuator bending. Then, the integrated device was fitted into a glove with the aim to explore and analyze finger movements (Figure 12e). By this design, the glove has the ability to test and evaluate finger stiffness or dexterity.

4.2. Smart Designing for Actively Deformable Apparels

The apparel field is developing rapidly due to the fashion and comfort requirements of humans. In addition, functionalization

has become one of the important design factors for people to consider. Flexible actuators exhibit excellent flexibility and are easy to integrate with textiles. Increasingly, researchers have integrated these systems into the design of smart apparels to achieve new functions, such as active deformation. In this section, we will mainly elaborate on two aspects: functional compression apparel and smart fashion design.

4.2.1. Functional Compression Apparels

Functional compression apparels are applied ever more in daily lives. For the current functions of apparels, compression controlling is a crucial challenge.^[200] Researchers have tried to combine flexible actuators with apparels. This approach enables dynamic compression apparels with controllable activation, suggesting applications ranging from assisted medical apparels to space suit design and more.^[13,199] These apparels can cooperate with humans to shape a better future.

Auxiliary Medical Compression Apparels: Flexible actuators have been widely researched in the auxiliary medical field to achieve controllable compression. For instance, Pourazadi et al.^[225] designed an active compression bandage for lower extremity venous insufficiencies, which was based on dielectric elastomer actuators. The authors considered the compliancy of human legs and simulated the interaction with human calves (**Figure 13a**). Kumar et al.^[200] presented a thermal-sensitive memory polymer actuator prototype to simultaneously heat and pressurize for achieving the desired compression, as shown in Figure 13b.



Figure 13. a) The calf and its several different regions to closely evaluate the interaction between an active compression bandage and the calf. Reproduced under the terms of the CC-BY 4.0 License.^[225] Copyright 2015, The Authors. Published by BioMed Central Ltd. b) The experimental set-up for the pressure measurement of the smart orthopedic compression device developed by Kumar et al. Reproduced with permission.^[200] Copyright 2016, Elsevier. c) A high-level V2Suit system architecture for space habitation and exploration developed by Duda et al. Reproduced under the terms of the CC-BY 4.0 License.^[226] Copyright 2015, Duda, Vasquez, Middleton, Hansberry, Newman, Jacobs, and West. d) The system architecture of the affective tactile jacket developed by Arafsha et al. Reproduced with permission.^[207] Copyright 2013, Springer Nature.

The compression can be switched freely between the static mode and dynamic mode. Furthermore, to achieve controllable pressure gradients, Edher and Salehian^[14] connected dielectric elastomer actuators with a belt mechanism to achieve actively cyclic compression, creating a pressure gradient of ≈ 10 mmHg. These advanced studies will provide a direction for the commercialization of auxiliary medical compression apparels.

Space Suit Design: Positive countermeasures are required to ensure the sensing and actuating performance of astronauts when performing the key missions in space. Based on this necessity, the "Variable Vector Countermeasure Suit for Space Habitation and Exploration" concept was proposed, [226] and a platform of integrated sensors and actuators was designed to improve the health and performance of astronauts, as shown in Figure 13c. Holschuh and Newman^[228] integrated NiTi shape-memory alloy coil actuators into compression apparels used for space medicine and extravehicular activity (EVA), which aim to solve the common problem of difficulty with $d_{\rm on}/d_{\rm off}$. Moreover, Choo and Park^[229] proposed a sublink mechanism based on rotary or linear actuators, and the enabled robotic pilots can withstand heavy loads while performing actions. The effectiveness of the wearable robot was tested and verified. These studies will provide a more convenient and comfortable space experience for astronauts.

4.2.2. Smart Fashion Design

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Fashion and dynamic deformation designs are developing trends in current apparel design. Recently, researchers and industrial groups have focused on the design and commercialization of functional apparels. The cross-collaboration between fashion apparel design and smart materials is undoubtedly an appealing field of efforts. Flexible actuators integrated in apparels will bring new functions for smart fashion design. For instance, Arafsha et al.^[227] designed an intelligent tactile jacket based on thermal and vibration actuators, as shown in Figure 13d. The proposed jacket system can support multiple interactions with humans including hugs, pokes, tickles, and touches. First Rogale et al.^[230] designed a clothing architecture based on sensors and actuators. The clothing can independently and continuously monitor and regulate thermal insulation properties according to external and internal environmental changes. In addition, to achieve a qualitative and quantitative assessment of the comfortable level of a garment, Ogata et al.^[231] developed a dummy robot system of clothing based on tactile sensors, linear actuators, and rotating servomotors, acting via the deformation mechanism; the system can measure the clothing pressure on the abdominal area and realize various deformations of the abdominal area and various trunk poses while further evaluating the comfort or discomfort of clothing. These studies have contributed to the diversification of smart wearable technology.

4.3. Soft HMI Robots

Soft HMI robots are emerging that are heralded to bring a revolution in the interactions between humans and machines. As an indispensable component of HMI robots, flexible actuators enable the bidirectional functionalities of perceiving an external

4.3.1. Wearable Manipulation Robots

Rapidly developed wearable manipulation robots offer a new paradigm to achieve HMI, which aims to offer safer, more complex, and more compliant functions.^[60] The shape-changing abilities of flexible actuators are extremely beneficial to manipulations in unknown environments.^[206]

Soft Robotic Grippers: Researchers have focused on flexible actuators for the application of gripping robotics, based on their superiority over rigid grippers for grasping objects with unusual shapes and contacting with environments softly.^[208] For example, Shian et al.^[15] utilized bending actuators to design gripping robots that were framed by adding predesigned stiff fibers or strips to guide the bending direction of the actuators. AbuZaiter et al.^[204] reported a microgripper based on SMA actuators, whose maximum generated actuation force is up to 100 mN, which is sufficient to move a small object. Furthermore, Li et al.^[208] proposed a soft robotic gripper based on silicone rubber actuators and a pack of particles. Since the stiffness of the gripper is proportional to the air pressure of the actuators, the stiffness is adjustable. The experimental results showed that additional other operations can be accomplished by soft robotic grippers.

Other Robotic Manipulators: Researchers have also investigated other types of robotic manipulators. Vikas et al.^[206] developed a motor-tendon robot, with a locomotion ability, by the 3D printing method. The flexibility of the robot was further studied by contacting objects with different shapes and friction mechanisms. Shi et al.^[43] developed a hand-like manipulator based on photothermal hydrogel actuators that is capable of localized movement, wireless remote control, and flexible deformation. Yuk et al.^[233] developed a high-speed and large-force robot based on hydrogel actuators, with the capability of optically and sonically camouflaging in water. The authors further demonstrated that the robots can accomplish further remarkable actions, such as swimming, kicking soft balls, and even catching fish in water.

4.3.2. Haptic Feedback Robots

Haptic feedback plays an important role in virtual reality and HMI paradigms. Haptic feedback offers the tactile perception of interacting with objects for users, such as grasping, manipulation, learning, and user response.^[234–236] With respect to flexible actuators exhibiting a dynamic response, researchers have intensively used these devices in haptic feedback robots to improve user experiences. For example, Smith et al.^[235] presented a realistic tactile feedback theory based on skin sensing capabilities, tactile perception principles, and tactile stimulation techniques. Furthermore, the authors designed a haptic keypad with this method.^[237] Aimed to improve the tactile feedback function, the researchers used piezoelectric actuators to simulate the typing experience of an actual keyboard. Hwang et al.^[238]





proposed a miniature haptic ring that used SMA wires as actuating components to respond to the force of the user's finger pads. In addition, Chen et al.^[239] developed a self-contained haptic interface prototype that provided precise vibrotactile and force feedback through integrated soft actuators. The results show that the system enhances the reality of HMIs. The aforementioned designs have provided inspiration for creating novel products with more realistic haptic feedback.

4.3.3. Bioinspired Robots

Creatures in nature have developed unique physiological structures after natural selection; their natural functionalities are typically far superior to manmade machinery and equipment. Inspired by these beings, researchers have designed many types of bionic robots based on rapidly developed actuating technologies.^[240] In this section, we will introduce several typical application prototypes by taking animal-bioinspired robots and plant-bioinspired robots as examples.

Animal-Bioinspired Robots: Animals in nature possess a variety of functions and characteristics due to natural selection. Researchers have conducted extensive research on bioinspired robots inspired by animals swimming, flying, crawling, etc. For example, Holley et al.^[205] proposed a self-stabilizing swimming robot that can control its swimming depth and motions without external intervention. The propulsion of the bionic swimming robot was based on its "fin" or cantilever angle of repose, providing speeds of up to 42 μ m s⁻¹. Furthermore, to develop entirely soft, autonomous robots similar to an octopus,

Wehner et al.^[60] reported a solely soft robot that achieves untethered operation, as shown in **Figure 14**a. The synergy between fuel and microfluidic logic powers, controls, and automates the operation of the soft robotic system. Inspired by the crawling and jumping of animals, Hu et al.^[47] developed a clawer-type robot based on optical actuators, which have the ability to mimic multiple actions, such as moving fast, crossing obstacles, and climbing steps (Figure 14b). Further, the authors proposed a soft jumping robot to mimic the gymnast's somersault (Figure 14c).^[32] The experimental results reveal the potential applications for the various biomimetic robots. The aforementioned integrated design and fabrication approaches have laid the foundation for the development of fully soft bioinspired robots.

Plant-Bioinspired Robots: Inspired by the natural phenomenon in which plant tendrils and petals can produce motion patterns spontaneously under the external stimuli of sunlight, humidity, or other atmospheric conditions, researchers have also conducted extensive research on plant-bioinspired robots. For instance, Wang et al.^[241] proposed a LC actuating strategy to synthesize plant tendril biomimetic materials with the ability to perform two different 3D reversible transitions by means of regulating the wavelength of light stimulation. In addition, Han and Ahn^[191] developed several deformable flowers based on a loop-linked structure, such as lily-like, daffodil-like, and calla-like flowers, with the ability of deforming in different transformation modes, as shown in Figure 14d. These advanced studies have made great contributions to the further development of the soft bioinspired robotic field.



Figure 14. a) Actuation of the octobot developed by Wehner et al. Reproduced with permission.^[60] Copyright 2016, Springer Nature. b) The crawlertype "robot" developed by Hu et al. Reproduced with permission.^[47] Copyright 2015, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. c) The soft jumping robot induced by light. Reproduced with permission.^[32] Copyright 2017, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. d) Blooming knitted deformable flowers developed by Han and Ahn. Reproduced with permission.^[191] Copyright 2017, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. d) Blooming weinheim.



5. Future Perspectives

The development of soft wearable robotics is impacting the fundamental and applied researches of several fields, such as medicine and rehabilitation, smart apparel design, and soft HMI. Developing a flexible actuating technology that can be processed and integrated by advanced methods will empower soft wearable robots with new features and functions. Benefitting from a large deformation, multiple degrees of freedom in motion, and the flexibility of actuators, these devices are anticipated to bring a new generation of soft wearable robotics that complement the existing rigid robotic technologies and play an important role in specialized tasks that classic rigid robots cannot achieve, such as MIS, controllable drug delivery, soft HMIs, and smart designs for actively deformable apparel. Currently, several integrated soft robotic system prototypes, which are usually made of commercial rigid or semirigid components, have already been preliminarily tested on animals or humans and have provided valuable experience for the further development of soft robotic engineering and technology. To realize the vision of wearing robots like clothing, flexible actuators and other key components fabricated with textile-compatible and biocompatible materials are crucial. However, such components are still at the embryonic stage of commercial application. Among diverse soft robotic application studies, several challenges persist such as size (large scale), stability, and full flexibility. In contrast, these challenges also represent promising opportunities for multidisciplinary integrations to create a new generation of soft wearable robots. To develop new technologies for soft wearable robotics, multiple existing technologies need cross-collaboration between fields, such as materials science, engineering control, and apparel design. The blooming development of the soft wearable robotic field is just beginning, and it will further evolve based on our deeper and more exhaustive comprehension of the fundamental science behind flexible actuators, wearable robotics, and soft HMIs.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

actively deformable apparels, flexible actuators, medical robots, rehabilitation assistance robots, soft human-machine interaction robots

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