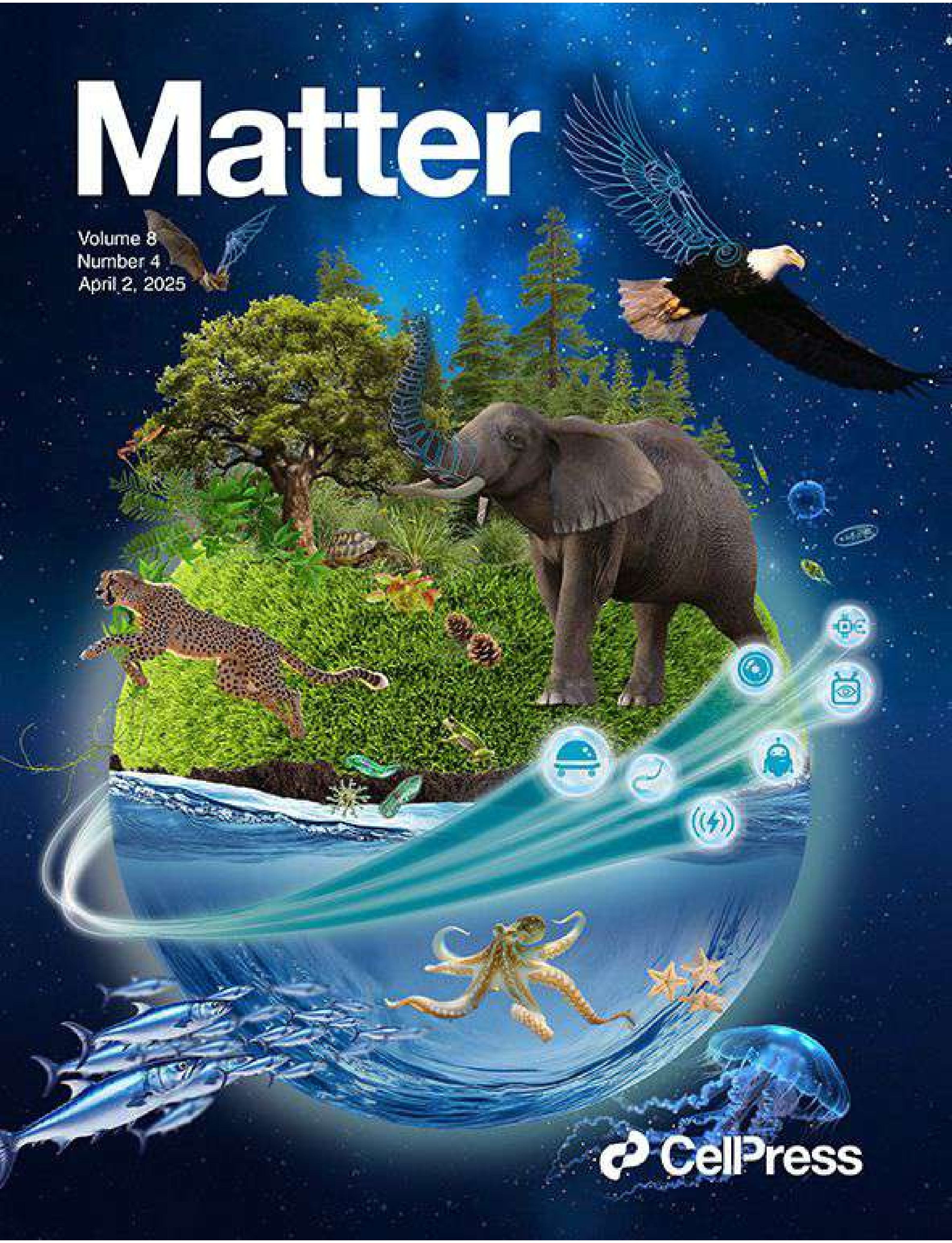
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Perspective

Bioinspired and biohybrid soft robots: Principles and emerging technologies

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PROGRESS AND POTENTIAL Bioinspired and biohybrid soft robotics represent a transformative frontier in materials science and engineering, drawing inspiration from the natural world to develop adaptable, multifunctional, and autonomous robotics systems. By combining biological principles with new soft materials and stimulus-response actuation strategies, researchers have made significant progress in mimicking natural movement, responsiveness, and adaptability of different biological species. They have not only enhanced our understanding of fundamental biomechanics but also accelerated the development of more efficient, sustainable, and functional soft robots. This perspective focuses on bioinspired and biohybrid soft robotics and provides in-depth discussions about fundamental principles of soft robots and designs inspired by different biological models from animals, plants, and microorganisms. A detailed overview is provided in terms of the latest progress of soft robotics in materials, sensing, control, actuation schemes, and other allied technologies. We further illustrate the development trends and myriad applications of soft robots inspired by different biological models, providing a unique perspective for future research and practical adoption.

SUMMARY

Soft robots have drawn increasing attention due to their inherent flexibility, deformability, and adaptability. The natural world, with its evolutionary refinement, presents the best source of inspiration for building soft robots. Creatures with sophisticated soft bodies and delicate mechanisms can be ideal biological models. This perspective focuses on bioinspired and biohybrid soft robots, providing a comprehensive review of the latest research in this area. We introduce the state-of-the-art principles of soft robots according to actuation, material selection, and sensing techniques. Based on biological classification methods used in nature, current research progress on biomimetic soft robots in animals, plants, and microorganisms is described. Emerging areas of interests are also highlighted for different biological species. Additionally, this paper explores the potential application areas of soft robots across various domains, outlining future challenges and ongoing developments.

INTRODUCTION

As robots become a ubiquitous part of our daily lives, the way they are controlled and actuated is undergoing rapid changes. Advances in computer vision and machine-learning techniques, particularly those leveraging the latest deep-learning methods, have significantly enhanced the perceptual and decision-making capabilities of robots. In parallel, exciting advances in materials science and the adoption of bioinspired design principles are radically changing the embodiment of robotics. Historically, robots were invented for working in factories, and the field of robotics progressed with the purpose of precise and controllable motion. Although such industrial robots are pervasive in many sectors, their limitations due to inflexible motion and rigid bodies

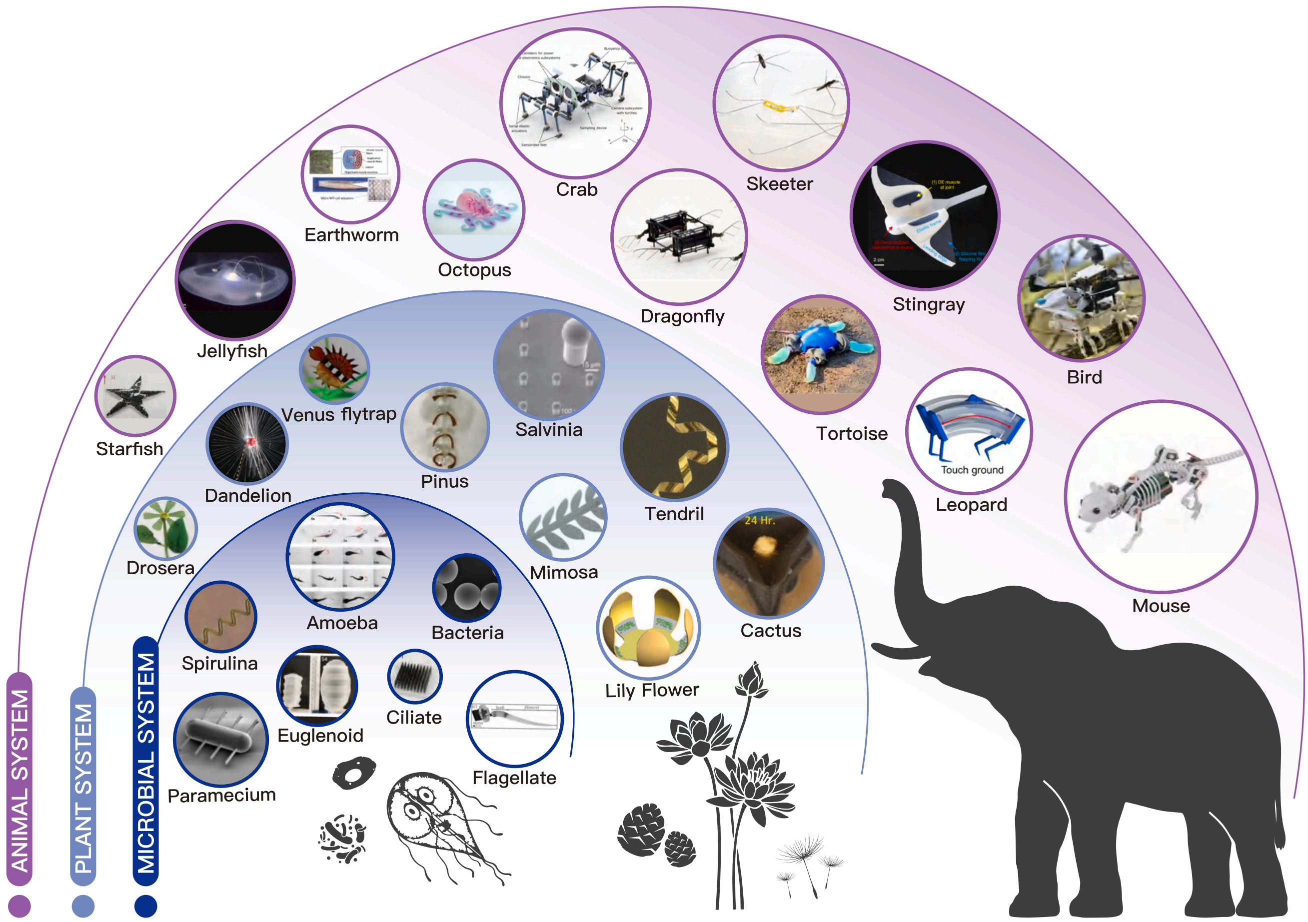

Figure 1. Soft robots inspired by animal, plant, and microbial systems
The natural world, with its evolutionary refinement, presents an ideal source of inspiration for building soft robots with innate flexibility, deformability, and adaptability.

are apparent when used outside of controlled environment such as factories. Soft robots, characterized by dexterity, deformability, and adaptability, represent a promising avenue to overcome these constraints.

Developing a sophisticated soft mechanism is crucial for crafting effective soft robots. We can draw inspiration from nature's ingenious creatures, which have undergone extensive evolutionary processes. Notable bio-models such as jellyfish,[1] caterpillar,[2] tendril,[3] flower,[4] and spirulina[5] offer valuable insights applicable to many sectors of robotics. In addition to bioinspired capabilities, soft robots can execute adaptive and flexible motions in unpredictable environments.[6] Recent advances include various soft actuators such as combustion,[7] ultrasound,[8] sunlight,[9] thermal,[2] and magnetic actuators.[10,11] 3D soft printing has been leveraged to manufacture soft actuators.[12–14] The integration of 3D soft printing simplifies the fabrication of these delicate actuators and introduces a novel power-supply method using inherent energy within the soft materials, eliminating the need for conventional rigid batteries.[15] Post-operation disposal poses a challenge, necessitating research into lifetime control and degradable soft materials.[16] The integration of biological components, such as muscle cells and receptors, into soft robots further generates biohybrids that leverage on nature's ingenious solutions directly.

The natural world offers a multitude of models as shown in Figure 1 for bioinspired designs, not only in the animal kingdom, which is most familiar to roboticists, but also in plants and the microworld of bacteria. This perspective summarizes the latest concepts and technologies in bioinspired and biohybrid soft robotics, discussing new trends across actuation, material, and sensing. It classifies bio-models into three categories: animal, plant, and microorganism, providing statistical insights into their popularity and research density, which guide future studies and developments. Subsequent sections detail the applications of various soft robots and discuss current challenges and limitations. The concluding remarks synthesize the key points of this perspective and offer directions for future advancements in soft and bioinspired robotics.

METHODS FOR SOFT-ROBOT ACTUATION AND SENSING

Owing to their flexible and deformable structures, soft functional materials can be designed for small-scale actuation and sensing

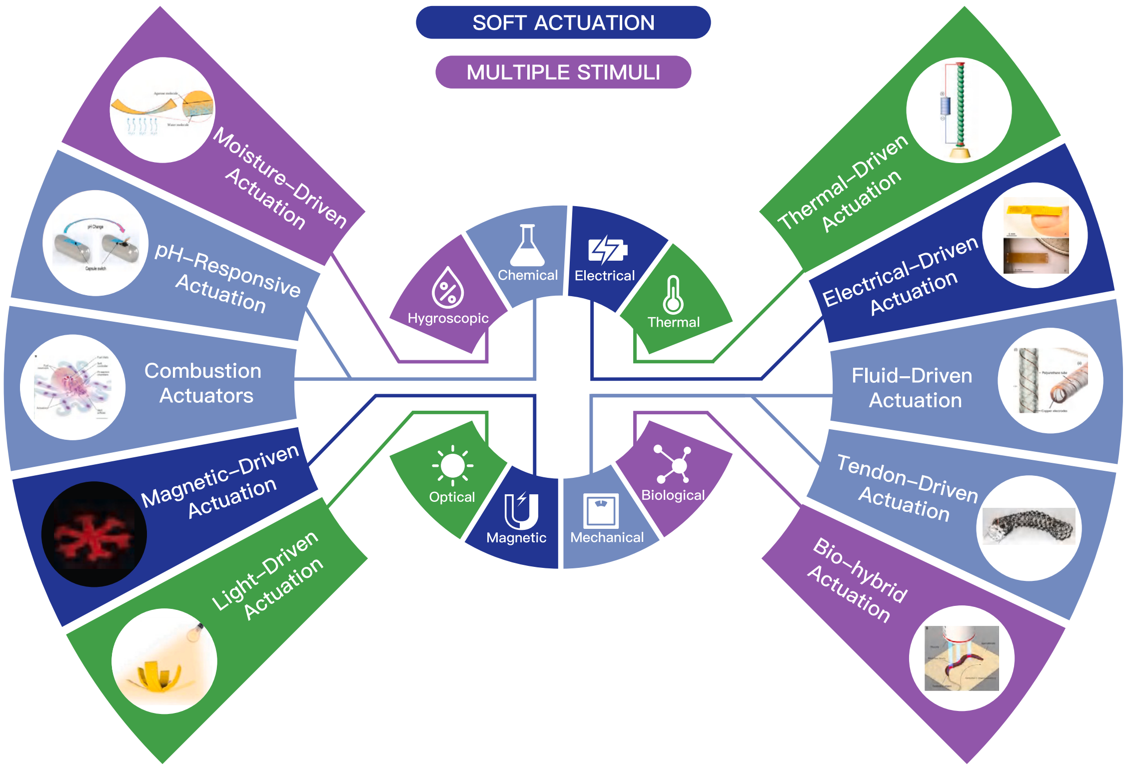

Figure 2. Schematic representation of actuation methods for soft robots categorized by their energy sources

Owing to their flexible and deformable structures, soft functional materials can be designed for small-scale drives with a range of stimulus responsiveness including hygroscopic,chemical,electrical,thermal, optical, magnetic, mechanical, and biological stimuli.

with a range of stimulus responsiveness, multiscale deformation, and diverse motion modes and functions. The driving forces of soft materials include, for example, magnetic, chemical, hygroscopic, electrical, thermal, and optical stimuli.[17,18] A schematic diagram of typical soft robots driven by different stimuli are presented in Figure 2, with their material characteristics and other related technical information summarized in Table 1.

Thermal actuators and sensors

Thermally driven soft robots can automatically respond to environmental temperature changes, increasing the self-adaptiveness made with soft actuators. These heat-responsive actuators can be precisely controlled on demand. For example, the temperature change required to actuate the soft actuators can be achieved by joule heating caused by electric current passing through conductive materials, also known as electrothermal effects. Additionally, using a laser to heat the actuator can precisely control the area being heated, achieving heterogeneous deformation. Soft materials that change shape in response to temperature variations can be used to develop this kind of soft actuator. For example, thin material layers with different thermal expansion coefficients, deposited on a soft substrate, can form a thermal soft actuator. Different expansion rates of the thin material layers upon heating cause the actuators to bend.[64–66] Therefore, thermally sensitive materials are extensively studied due to their unique thermal properties, such as thermal expansion ratio, melting point, reordering, and decomposition, making them promising candidates for constructing soft robots.[67]

Thermal actuators based on liquid-crystal elastomers

Liquid-crystal elastomers (LCEs) can undergo large and reversible shape changes when heated above the transition temperature, which is achieved by the alignment and reorientation of liquid-crystal molecules within their elastomeric matrix.[68] Wu et al. proposed an LCE-based soft actuator that solved the contradiction problem between thermal reprogrammability and stability. This smart swelling-heating method was introduced to enable repeatedly switching on and off siloxane network dynamics in LCEs, resolved the trade-off problem between the excellent performance in stability and thermal reprogrammability.[69] By combining LCEs with a soft and stretchable thermoelectric layer, a soft-robotic walker was developed and able to walk in response to the heating and cooling control. The thermoelectric layer, which is sandwiched between two layers of LCE, comprises semiconductors embedded within a 3D-printed elastomer matrix and wired together with eutectic gallium-indium (EGaIn) liquid-metal (LM) interconnects. This configuration allows the layer to harvest energy from the thermal gradient between the two LCE layers, thus leading the conversion of thermal energy into electrical energy.[26] In addition to motion control, Liu et al. introduced a soft actuator based on LCE incorporating tetraarylsuccinonitrile (TASN) that exhibits the reversible color-changing, morphing, and self-healing ability in response to heat and external compression. The color-changing behavior is derived from the recombination of carbon radicals within the TASN units of the polymeric network. Meanwhile the self-healing function is facilitated by the dynamic covalent chemistry in the TASN-LCE material.[70] In certain applications, LCEs can be utilized as inks for 3D printing, allowing the additive manufacturing of intricate structures for soft robots. Kotikian et al. developed a thermally responsive soft robot with 3D-printed active hinges using LCE inks, which can perform reversible shape-morphing and programmable self-propulsion abilities. The design incorporates bilayer-structured LCE hinges, which are printed in orthogonal orientations. This arrangement induces anticlastic bending and effectively reduces the energy required for bending motions.[71] In another study, researchers developed a printed LCE soft crawling robot designed with an eccentric hinge, showing the ability to sustain oscillation under a constant thermal field. The eccentric design of the hinge produces asymmetric bending of the robot, facilitating movement. By adjusting the substrate friction, the motion characteristics and modes of the robot could be modified. This design provides a simple and effective method for deployment in constrained environments, such as those encountered in aerospace and medical fields.[72]

Thermal actuators based on thermal-sensitive hydrogels

Hydrogels, which consist of water and hydrophilic polymer chains arranged in a network structure, are promising materials for soft robots due to their flexibility and responsiveness to environmental stimuli. Temperature changes could induce the temperature-mediated hydrophilic-hydrophobic transition of the polymer chains, causing the desorption and absorption of water that drives material deformation. Two distinct categories of hydrogels can be used for creating thermally responsive soft robots. The first category includes hydrogels with a lower critical solution temperature (LCST), such as poly(N-isopropylacrylamide) (PNIPAM), which perform shrinkage when temperature rises above the critical point.[73] The second category includes hydrogels with an upper critical solution temperature (UCST), such as poly(acrylic acid-*co*-acrylamide), which can swell when over the critical temperature.[74] Lo et al. introduced a photothermally responsive material composed of nano-structured thermal-responsive hydrogel PNIPAM and the light-absorbing polymer polypyrrole (PPy). This nano-structured PNIPAM offers significantly higher stretchability (>210%), a faster response rate (six times swifter), and a larger volumetric change ($\Delta V/V = 70\%$) compared with conventional PNIPAM. The temperature of the hydrogel can be simply regulated by adjusting the light intensity, with PPy converting light energy into heat, thereby changing the temperature of the PNIPAM and inducing a volumetric change.[75] The properties of PNIPAM also inspired the development of a hydrogel-based soft actuator designed for temperature regulation. Mishra et al. introduced a 3D-printed, finger-like elastomer actuator consisting of a PNIPAM body embedded with microporous polyacrylamide (PAAM), which exhibits the ability of autonomic perspiration. More specifically, when the environment temperature is lower than $30^\circ C$, the micropores can close sufficiently to prevent a loss of heat energy. However, as the temperature rises above $30^\circ C$, the micropores gradually dilate, enabling the perspiration process, like human sweating for the removal of redundant heat.[29] Another group introduced a gradient hydrogel to provide self-sensing capabilities, ultrafast thermo-responsive actuation, and high sensitivity for interaction between soft and hard robotic components. This gradient hydrogel was achieved through a wettability difference method by incorporating M_oO_2 nanosheets during copolymerization of PNIPAM and sodium alginate monomers. This process formed a hydrophilic disparity between the two sides of the hydrogel, enabling it to respond dynamically to environmental changes and facilitating more effective remote interactions in robotics applications.[76]

Thermal actuators based on shape-memory alloys

Shape-memory alloys (SMAs) are a class of smart materials that exhibit unique properties. Characterized by shape-memory effect and superelasticity, SMAs are able to deform when at a lower temperature and restore to their initial shape when heated above a higher temperature.[77] Based on these properties, SMAs have significant potential for applying to emerging soft robots. In one study, a sub-millimeter smart soft actuator was developed, utilized two-photon polymerization, and was embedded with SMA wires. The carbon nanotube (CNT) layer was additionally deposited to increase the thermal absorbing efficiency, and polydimethylsiloxane (PDMS) coating was applied to increase the elasticity. The morphing modes can be changed when altering the direction of the scaffold lamination.[19] In another application, Jin et al. developed an SMA planar actuator with various capabilities, including step response, position tracking, and motion control.[78] Similarly, SMAs can be used as artificial muscle for soft wearable robots, assisting wrist motion and reacting to the temperature control system.[79] A high-accuracy SMA actuator for real-time medical robotics applications was introduced by Ding et al. The SMA was designed as a spring, acting as the driving part, and it was actively actuated by heating current and cooling air systems.[80]

Thermal actuators based on shape-memory polymers

Shape-memory polymers (SMPs) can return to their original shape after being deformed, triggered by a thermally induced phase transition.[81] One study involved a soft pneumatic robot with an inextensible SMP layer that remains stiff at 25°C but softens at 70°C. Temperature control around the SMP is achieved through an integrated electrical heating circuit and a water-cooling channel, enhancing body stiffness and offering various loading capacities while maintaining flexibility and adaptability.[23] Spinning fibers or filaments made of SMPs can form twisted and coiled artificial muscles.[82,83] Upon heating, twisted and coiled polymer actuators (TCPAs) undergo two simultaneous processes: thermal-induced expansion and material softening. The thermal expansion, particularly radial swelling, initiates the untwisting of the fiber and alters the geometry of the helical structure. Concurrently, material softening, especially prominent in the amorphous regions, facilitates the reconfiguration of the helical indices. These combined effects transform the material's thermal response into a linear contraction, forming the basis of TCPA actuation.

Thermal actuators based on phase-change materials

Phase-change materials (PCMs) can also be utilized for actuation, have a low boiling point, and can maintain a liquid state at low temperatures but transition to a gas state when heated, resulting in significant volume expansion.[31,60] Based on this property, Tang et al. proposed a balloon-shaped inflatable miniature

Table 1. Summary of soft actuators based on different stimulus, materials, and their technical information

Stimulus	Material	Response times	Energy efficiency	Power density	Motion	Comments	Reference
Heat	SMAs	sub-second to seconds	<10% (Carnot efficiency)	50 kW/kg	bending (sheet 5.5 mm × 200 μm × 100 μm) 80°	1. energy efficiencies are generally low 2. actuation frequencies heavily depend on cooling conditions	Lee et al., Arias Guadalupe et al., Park et al., and Hollerbach et al.[19,20–22]
	SMPs	sub-second to seconds	1-2%	2.8 kJ/kg	bending (2D sketches 108 mm × 22.5 mm × 14.3 mm) 50°		Zhang et al., Jia et al., and Ahn et al.[23–25]
	LCEs	<0.2 s	20%	400 W/kg	bending (cantilever 50 × 14 mm) ±27°		Zadan et al., He et al., and Davidson et al.[26–28]
	hydrogels	several to more than 10 s	N/A	107 w/kg	bending (actuator) 150°		Mishra et al. and Li et al.[29,30]
	PCMs	dozens to hundreds of seconds	N/A	175.2 J/g	locomotion (swimmer) 0.24 m/s		Tang et al. and Yoon et al.[31,32]
Moisture	carbon based	0.8 s	N/A	0.08 W/kg	bending (cantilever 1 cm × 2.5 cm × 8 μm) 90°	1. harvest energy from environments so that the requirement of onboard power is diminished 2. their performances strongly depend on environmental conditions and therefore have low controllability	Wei et al. and Ge et al.[33,34]
	polymeric	110 ms	N/A	4 J/kg	locomotion (sheet 25 mm × 5 mm × 30μm) 6 mm/s		Shin et al., Cecchini et al., and Xing et al.[35–37]
	hydrogel based	21.5 ms^{-1}	1.48%	~18 mw/g	locomotion (sheet 30 mm × 4 mm) 66 mm/min		Li et al.[38,39]
Light	photochemical	0.5 s	~10%	25.1 kJ/m^3	locomotion (disks ϕ 400 μm × 50 μm) 40 μm/s	1. can achieve remote control with high precision 2. diminished requirement of onboard power 3. may not be suitable for field robots due to special need for optical components and exposure to the light beam	Palagi et al. and Tahir et al.[40,41]
	photothermal	0.08s	36.42%	10 kJ/m^3	bending (cantilever 3 mm × 1 mm × 7mm) 90°		Zhao et al., Li et al., El-Atab et al., and Zhu et al.[42–45]
Magnetic	soft-magnetic	100 m	~70%	0.25–1.2 J/m^3	contraction and expansion (cylinder ϕ11 × 130 mm) 60%	1. can achieve remote control, especially suitable for clinical settings 2. may not suitable for field robots as the magnetic field attenuates fast with distance	Nguyen and Ramanujan[46]
	hard magnetic	milliseconds	~80%	22.3–309.3 kW/m^3	leap (auxetic 45 × 32.5 mm) 250 mm/s		Kim et al., Hu et al., and Zhang et al.[11,47,48]
	superparamagnetic	60 s	N/A	5–10 J/m^3	contraction and expansion (sheet) 60%–90%		Wu et al.[49]

(*Continued on next page*)

Table 1. *Continued*

Stimulus	Material	Response times	Energy efficiency	Power density	Motion	Comments	Reference
Electric	EAPs	sub-second to seconds	2.5%–3%	2.44 kJ/m^3	locomotion (swimmer 1.2 × 0.4 cm) 0.53 BL/s	1. high controllability 2. may achieve high actuation frequency	Ahn et al., Ko et al., and Ren et al.[25,50,51]
	DEs	500 Hz (bandwidth)	∼26%	0.02 kJ/kg	locomotion (climbing) 63.43–88.46 mm/s	3. electrochemical reaction may degrade the lifetime and performance	Ahn et al. and Gu et al.[25,52]
	hydraulically amplified self-healing electrostatic	40–123 Hz (bandwidth)	19%–21%	80–614 W/kg	contraction and expansion (sheet, curling) 20%–124%		Rothemund et al.[53]
Chemical	pH responsive	1.2 s	N/A	287 kJ/m^3	contraction and expansion (flytrap inspired)	1. low controllability 2. high energy density 3. low actuation frequency	Wang et al. and Li et al.[54,55]
	combustion-driven	0.2 s	∼4%	9.1 kW/kg	locomotion (jumping) 1.12 m		Aubin et al. and Bartlett et al.[7,56]
Mechanical	cable driven	sub-second	85%	N/A	locomotion	1. can realize accurate displacement and force control 2. high energy efficiency 3. bulky support peripherals	Kraus et al.[57]
	fluid-driven	50 ms	10%–60%	10–10^3 kw/m^3	bending (pneumatic networks) 360°		Mosadegh et al., Ainla et al., and Miriyev et al.[58–60]
Biohybrid	cells/tissues	sub-second to seconds	20%–40%	1–10 kw/m^3	locomotion (skeleton) 800 μm/s	1. materials are biocompatible 2. limited durability and stability 3. hard to be integrated in conventional robotic systems	Guix et al., Fang et al., and Madden et al.[61–63]

soft robot. This robot was filled with a biocompatible liquid (Novec 7000) that has a low boiling point ($\approx 34^{\circ}C$) to enable thermally responsive locomotion and inflation. This design enables the robot to achieve an output force of up to 70 N and a work capacity of up to 175.2 Jg^{-1}. The research demonstrates the potential applications of this miniature soft robot in medical procedures, including angioplasty and reversible bistable stents.[51] In another study, a programable thermochromic soft actuator with a bilayer structure was introduced by Zhong et al. Heptafluoro-1-methoxypropane was selected as the PCM due to its low boiling point of $34^{\circ}C$, while Ecoflex 0035 fast was chosen as the silicone matrix material to achieve a fast curing time of 5 min. This design allows the soft actuator to deform greatly through extreme volume change and to change colors via the reversible reactions of embedded thermochromic microcapsules.[84] Sogabe et al. developed a soft robot incorporating a silicone body with an internal cavity filled with fluorine-based inert liquid FC-72, which has a boiling point of 56°C. This design allows the robot to morph variably at different water temperatures. When the surrounding temperature exceeds 56°C, the FC-72 rapidly evaporates, causing the silicone body to expand and bend toward the thicker wall, aided by the low Young's modulus (0.07 MPa) of the silicone and the rapid phase change of the FC-72.[85] A thermo-responsive soft actuator demonstrates excellent bending ability was developed by Kang et al. based on volume expansion/retraction accompanying liquid-vapor phase transition of PCMs. The multilayer structure was applied and consisted of an ethanol-infused nanofiber (NF) mat as PCM encased in a biocompatible elastomer. This design allows the actuator to develop strains up to 200% and bending angles near 180° when approaching the boiling point.[86] In another study, a soft thermo-pneumatic actuating module that operates based on the thermally controlled gas-liquid phase transition was introduced. Novec 7100 Engineered Fluid with a boiling point of $61^{\circ}C$ was used as the PCM, and thermally conductive silicone rubber was used to enhance the thermal efficiency. Based on this method, a thermally responsive soft gripper and an entirely untethered soft earthworm were designed and showed their advantages in deflation rate.[32]

Thermoreceptors

Organisms use specific thermal receptors to sense external temperatures. The artificial soft thermal sensor can also play an essential role in various applications. It could be produced from a variety of materials, such as films, rubber, hydrogels, and aerogels. Wang et al. described the structure and material design of a soft sensor that used a thin-film thermistor to achieve thermal sensation and proposed a novel method for temperature and strain compensation.[87] Oh et al. developed a skin-attached temperature sensor using a microstructural adhesive that mimicked the suckers of an octopus. The sensor exhibited a sensitivity of $2.6\% \cdot {}^{\circ}C^{-1}$ between 25°C and 40°C. Subsequently, a strong adhesive, comprising PNIPAM-thermosensitive hydrogels, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate, and CNTs was developed that enabled the skin-attached sensor to achieve stable temperature sensing over long periods of time.[88] Mao et al. used graphene aerogel spheres (GASs) to create a flexible temperature sensor with a resistance temperature coefficient of $2.2\% \cdot {}^{\circ}C^{-1}$, five times that of commercial resistance thermometers.[89] Li et al. were inspired by the abundance of various ionic compounds in the body fluids of plants and animals and introduced zwitterions into a hydrogel. The polyelectrolyte molecular chains could ionize a large number of free ions, thereby reducing the freezing point of the water phase. The hydrogel exhibited an ultra-high electrical conductivity of 0.041 $S \cdot cm^{-1}$ and could withstand a low temperature of $-37.1^{\circ}C$.[90]

Soft actuators and sensors triggered by moisture

Humidity or moisture level is a critical environmental factor in nature, based on which many organisms have developed self-adapting mechanisms. Inspired by these adaptive creatures, researchers have explored moisture-driven soft robots across various domains. In order to be responsive to changes in air moisture or humidity, soft materials must possess the ability to absorb water molecules from the air and exhibit distinct changes in their physical properties when moisture condensation occurs. Typical moisture-responsive materials used to construct the humidity-driven soft actuators include graphene oxide (GO),[91] reduced GO (RGO),[92] MXene,[93] polyvinyl alcohol (PVA), sodium alginate,[94] and modified PPy.[95] Those moisture-responsive materials combining with different microstructure and macroscopic design could perform various locomotions.[96,97]

Carbon-based moisture-driven actuators

GO is a highly favored material for constructing moisture-driven soft actuators. The moisture sensitivity of GO-based materials is mainly due to the interactions between water molecules and the oxygen functional groups on the surface of GO.[96] As the surrounding humidity rises, water molecules establish hydrogen bonds with the oxygen functional groups on the GO surface, causing internal tensions that result in a modification of the material's structure. Wei et al. developed a complex composite film using GO that is sensitive to moisture. This coating was designed to enhance the sensitivity, durability, mechanical strength, and electrical conductivity of a soft robot used in construction. In addition to GO, the composite also includes one-dimensional cellulose NFs (CNFs) and CNTs. While GO and CNF are sensitive to moisture, CNT is resistant to water. The CNF/GO/CNT composite film created a distinct hydrophilic-hydrophobic hybrid matrix with several porosity structures, which effectively increases the rate at which water molecules are exchanged and hence improves the response time.[33] The moisture-responsive SMPs have been extensively studied as alternative possibilities for GO.

Polymeric moisture-driven actuators

Polymeric materials are widely used as moisture-responsive materials for soft robots. These polymers are soft, elastic, and malleable and can become sensitive to changes in moisture or humidity when combined with hygroscopic substances. One typical moisture-sensitive polymeric material is polyethylene oxide (PEO), which is hydrophilic and has a high capability in water absorption. In one application, hygroscopically active fibers composed of PEO and cellulose nanocrystals (CNCs) have been introduced.[35,36] A type of bilayer-structured soft actuator, featuring a PEO-based active layer and a hygroscopically inactive polyimide (PI) layer, has demonstrated capabilities in various forms of locomotion, with PEO fibers aligned in one direction.[35]

Hu et al. introduced a planar polymer film that shows the dual-responsive characteristics. This 2D PEO/sodium alginate (SA)/tannic acid (TA) thin film can be converted to 3D shape by increasing the moisture level of the surroundings. The thin film was manufactured from PEO and SA with a weight ratio of 9:1, with the addition of TA to enhance the mechanical properties and enable the photo-to-thermal conversion. It exhibits a tensile strength of 8.4 MPa and a fracture strain of 1457%.[98]

In addition to PEO, a particular study selected poly(ethylene-*co*-acrylic acid) as the polymer to analyze. They achieved moisture-responsive movement by including hygroscopic patterns produced from a coordinating network of Fe^{3+} – carboxylate, which was created by exposing the polymer to UV light.[99] Researchers employed poly(3,4-ethylenedioxythiophene):poly (styrene sulfonate) (PEDOT:PSS) as the moisture-sensitive polymer and integrated it with the passive material PDMS to construct a soft actuator with a bilayer structure. Swelling and bending motions of the robot can be observed when different humidities are applied.[100] Hygroscopic PVA is another approach to developing a moisture-actuating soft robot. Xing et al. developed a reversible actuator by using silver nanoparticles (AgNPs) to connect the PVA with the flexible shape-memory polymer. The tri-layer composite was able to perform fast bending with good repeatability and stability.[37] PVA can also be combined with sodium alginate (SA) through layer-by-layer assembling to achieve uneven hygroscopic features along the thickness of the composite, leading to a large internal interaction force between layers, thus making directional motion controllable.[94]

Hydrogel-based moisture-driven actuators

Hydrogels are a class of material that can absorb large amounts of water, swelling when moisture or humidity levels change. Agarose, rich in hydroxyl groups and thus moisture sensitive, was chosen to construct a soft rolling robot. A single-layer agarose film formed the main body of a rolling robot that responds sensitively to slight humidity gradients, achieving controlled, rapid rolling locomotion. The soft rolling robot demonstrated its ability to withstand more than 1,000 cycles of hydration and dehydration without any degradation.[101] In another study, a self-healing glycerol hydrogel that is highly stretchable, ultra-tough, and robust was demonstrated. Due to the excellent dehydration resistance of the glycerol hydrogel, it was used to build a gripper to exhibit gripping, lifting, and releasing a ball by controlling the moisture level.[102] Li et al. introduced a special moisture-responsive yin-yang-interface actuator based on polyacrylamide (PAM) hydrogel. The actuator has a tri-layer structure; a layer of PAM hydrogel is attached with a moisture-inert polyethylene terephthalate (PET) layer by applying an interfacial poly(2-ethylhexyl acrylate) (PEA) adhesion layer. It can demonstrate programmable morphing motions with a fast response to moisture.[38]

Soft actuators and sensors triggered by light

Light, a fundamental energy source in the natural world, has been explored extensively for soft actuation. Light-driven soft actuators exploit the properties of photoresponsive materials, which include of host polymers and photoresponsive additives, through various mechanisms to induce photo-mechanical deformations. The physical and chemical properties of photoresponsive materials can change under different conditions, such as the wavelength and intensity of light. Depending on the triggering method, the reactions can be divided into directly and indirectly triggered photochemical and photothermal reactions.

Light-driven soft actuators based on photochemical materials

Light illumination can directly affect polymers with photoresponsive functional groups at the molecular level, leading to macroscopic deformations. Consequently, azobenzene and cinnamate functional groups are commonly added to polymers. The primary mechanisms for azobenzene molecules are photo-isomerization, where photo-isomerizable molecules integrated within the polymer undergo a reversible conformational change when exposed to specific wavelengths of light. This transition between isomeric states (e.g., from *trans* to *cis*) results in a significant alteration in molecular conformation, which induces internal stress within the polymer matrix, leading to mechanical deformation. LCE can utilize azobenzene molecules for light-induced deformations.[103–105] By harnessing the rapid response of azobenzene chromophores to specific wavelengths of light, researchers have been able to design repeatable and programmable LCE-based soft actuators.[106] Palagi et al. used structural light to drive an LCE ciliate-like robot. The robot was built using an LCE with long cylinders and flat disks, and its movement was controlled using periodic light.[40] Kizilkan developed a biomimetic transport microstructure composed of crosslinked LCEs containing azobenzene. When irradiated with 320- to 380-nm UV light, the azobenzene portion rapidly changed its molecular size depending on the azobenzene substituent. This size change was the result of reversible *trans cis*-isomerization. The film could be restored to its original shape using wavelengths in the range 420–480 nm.[107] Chen et al. used UV light to adjust the conductivity of a triphenylmethane leuconitrile (TPMLN) hydrogel, resulting in a 10-fold change in local conductivity.[108]

Cinnamate-based materials exhibit photoresponsive properties due to them undergoing a photodimerization reaction when under UV illumination, and the process is reversible. Rose et al. used UV illumination to deform and fix polymers containing cinnamon groups into predetermined shapes. The photoresponsive SMPs were processed into thin films. The film was then stretched by external stress and released by UV light of wavelength $\lambda > 260$ nm. The cleavage of newly formed photosensitive crosslinks could be induced using $\lambda < 260$-nm UV light, completing the preparation of the material.[109]

Light-driven soft actuators based on photothermal materials

Another important mechanism used in soft robotics is the photothermal effect, which involves the conversion of light energy into heat through the absorption by additives such as CNTs[110] or Disperse Red 1 acrylate (DR1A),[111] or through the coating layer, such as the polydopamine (PDA) layer.[27] These absorb near-infrared (NIR) light and convert photon energy into heat energy, thereby changing the polymer properties. In many cases, these two mechanisms coexist, contributing to the actuator's deformation. Combined with the self-blocking mechanism, where parts of the actuator shadow other parts from receiving light, the actuators can achieve cyclic motion, enabling rhythmic locomotion modes such as walking and swimming.[9]

Kanik et al. developed twin-shaped fibers composed of high-density polyethylene (PE) and a cyclic olefin copolymer elastomer (COCe) that could mimic human muscle fibers. Photothermal stimulation was performed using a modulated broadband wide-pulse light, and fiber expansion and contraction could be achieved by creating a driver based on the principle of differential expansion in the cucumber whisker compartment.[112] Zhao et al. reported a soft-sensitized material for conducting and photothermally responsive hydrogels. Uniform ductile conductive hydrogels synthesized using ice-templated cryopolymerization exhibited dense conductive networks and a highly porous microstructure. They achieved ultra-high electrical conductivity (36.8 mS/cm), high stretchability (170%), large-volume shrinkage (49%), and 30-times faster response than conventional hydrogels. Piezoresistive strain/pressure sensing and light/thermal actuation functions could be combined to integrate the sensing and driving of materials.[42] A popular structure for studying light-responsive soft actuation is the GO-based multilayer, favored for its photothermally active properties. Here, light is converted to heat, inducing the thermal expansion of materials.[113] A sensitive graphene actuator utilizing both GO and RGO demonstrated programmable motions under UV light. The photoenergy from UV light is absorbed by GO, which causes a temperature increase and a distinctive thermal expansion ratio, leading to the controlled deformation of the soft layer.[91] Additionally, this actuator type has shown excellent repeatability and durability.[96] Yang et al. integrated MXene nanomonomers with an LCE matrix to enhance photothermal conversion efficiency, fabricating a bioinspired omnidirectional light-tracking soft actuator with integrated sensing capabilities.[114]

Photoreceptors

Photoreceptor is one of the essential components for light-responsive soft robots and actuators. Zhao et al. fabricated stretchable optical waveguides using silicone composites coated with a transparent PU rubber. Light-emitting diodes and photodetectors were used to measure the optical power loss of the waveguide under different deformations. The sensor was integrated into a prosthetic hand to measure elongation, bending, and pressing actions. The shape, texture, and softness of the object could be determined.[115] Bae et al. described a stereovision artificial compound-eye system that simulated the compound eye of a praying mantis. The vision system comprised multiple microlens arrays and high-resolution sensors with a 180° field of view. Stereo vision was realized using a federation split-learning algorithm to process information corresponding to the system edge, accurate spatiotemporal object sensing, and optical flow-tracking capabilities.[116] Zhou et al. described a bionic pinhole compound-eye system that utilized hemispherical perovskite nanowire arrays and 3D honeycomb structures to achieve an ultrawide field of view of approximately 360°. Nanowires of length approximately 10 μm were manufactured by a micro-nano process. The spatial resolution of the compound-eye system was approximately 1°, and the response time was less than 10 ms.[117] Jamil et al. designed a flexible sensor with soft optical waveguides to measure the contraction and force of artificial pneumatic muscles. The variation in the axial size of the PAM was measured using a radial arrangement, the PAM force being measured in an axial configuration.[118]

Another category of optical sensors is based on matched photodiodes and phototransistors, which can be used to detect changes in light intensity, wavelength, or polarization. These devices convert light into electrical signals, enabling applications like light-based control and vision in soft robots. Recent advancements led to flexible and stretchable photodetectors seamlessly integrated into robot bodies. The Tactile Blep (T-Blep) is an optical soft sensor that can measure the stiffness and force of different materials. The sensor consists of an inflatable membrane with internal optical elements. The T-Blep can switch between stiffness-detection and force-detection modes by changing the pattern followed by the internal pressure of the membrane (force peak of 5.43 N and sensitivity up to 331 mV/N, stiffness detection accuracy of 97%).[119] Lo Preti et al. developed a fingertip-shaped soft optical sensor with optically transparent channels that relies on soft materials and sensor morphology to measure an applied triaxial force (volume 2.5 cm^3, sensitivity 0.34 N/mV and 0.09 N/mV to tangential and normal forces, F_{xy} and F_z with an R^2 of 0.93 and 0.98 within a sensing range of 4.05 N and 8.50 N). A coordinate transformation from a covariant to a cartesian reference frame is used to retrieve the direction of the tangential component of the force. The modulus of the force is then calculated using a linear model, followed by a component decomposition. The sensor was integrated into a compliant robotic hand as a proof of concept to demonstrate real-time operation in typical grasping tasks.[120]

Soft actuators and sensors triggered by magnetic fields

Recent research has highlighted the use of magnetic control as a popular method for actuating soft robots. The magnetically responsive properties of soft robots, including both the magnetization and magnetic moment direction, can be reversibly designed during the design stage and programmed during the manufacturing process, enabling versatile dynamic deformations under the control of a time-varying magnetic field.[121] This feature enables multimodal bioinspired locomotion modes accommodating various terrains.[47,122] This popularity stems from the ease of incorporating magnetic-sensitive material into the soft-robot body.

Magnetically responsive soft actuators

Magnetic soft materials represent a group of soft, deformable solids with magnetorheological, magnetoactive, or magnetic-sensitive properties, which allow for controllable morphing and programmable motions through the variation of an external magnetic field.[123] These materials typically include two key components: magnetic particles and a soft matrix.

The magnetic particles are often made from ferro-/ferrimagnetic materials and can be either magnetically soft or hard.[123–125] Soft-magnetic materials are characterized by high magnetic susceptibility and saturation magnetization but low remanence and coercivity (e.g., iron, nickel, or silicon-based iron alloy); hard-magnetic materials maintain a stable and permanent magnetic source once magnetized (e.g., alnico). The coercivity of these particles is significantly influenced by their size. When the size of the magnetically sensitive particles is smaller than a critical value, they exhibit superparamagnetic properties, characterized by very low coercivity and increased susceptibility to thermal fluctuations and relaxation (i.e., Fe_3O_4 particles).[123] For practical applications, particles based on iron oxide, such as hematite ($\alpha - Fe_2O_3$), maghemite ($\gamma - Fe_2O_3$), and magnetite (Fe_3O_4), are commonly used in constructing soft robots for biomedical, logistical, and various other purposes due to their low cost, biocompatibility, and ease of production.[126]

The soft matrix typically includes materials such as hydrogels, rubbers, silicones, and polyurethanes, serving as the scaffold for the artificial soft structure. These materials provide the necessary flexibility and support for magnetic actuation. A magnetic object will be subject to magnetic torque proportional to magnetic field strength and magnetic pulling force proportional to the magnetic field gradient. Embedded with magnetic particles, magnetic soft composites will deform when subjected to an external magnetic field due to the magnetic forces and torques transmitted to the polymer matrix. The dynamic deformation of the magnetic soft composite can be used for the actuation of soft robots. For instance, a magnetic soft robot was developed using an origami-inspired technique, integrating NdFeB particles with a PDMS matrix. The robot, constructed through 3D printing with a compound of NdFeB/PDMS (60 wt % NdFeB), demonstrated multidirectional movement and multi-dimensional deformations under an external magnetic field.[127] In another application, ferrimagnetic nanoparticles (Fe_3O_4) were used as the magnetothermal component in pneumatic artificial muscles and soft-robotic grippers. These particles generate heat upon exposure to a high-frequency alternating magnetic field (150 kHz), inducing the liquid-to-gas phase transition of water within a balloon. The heat from the Fe_3O_4 particles causes steam bubbles to form, increasing the internal pressure and enabling the robot to perform lifting and grasping actions without the need for compressors, valves, or other bulky actuation components.[128] Another study used LCE as the base matrix,[129] and the robot could react to both temperature changes and varying magnetic fields, leading to self-adaptive locomotion modes in different environments.

Magnetoreceptors

Living organisms can detect changes in magnetic fields. Migratory birds use magnetic fields to navigate during migration; sea turtles rely on magnetic fields to return to the beaches where they were born to nest; and fish, such as eels and sharks, migrate using magnetic fields. Magnetotactic bacteria use magnetosomes in their bodies to move and determine the optimal living conditions. Ozel et al. described a composite soft-bending drive module that incorporated curvature sensing. By combining flexible materials and embedded sensors, the drive module could detect the degree of bending in real time while performing a bending action.[130] Wang et al. proposed a three-axis flexible tactile sensor based on magnetic fields, triaxial force sensing using flexible materials, and magnetic sensing elements. The moving least-squares method was used to decouple and convert the magnetic field signal to eliminate nonlinear and crosstalk effects. A resolution of 1.42 mN was achieved for normal force measurements and 0.71 mN for shear force measurements, demonstrating good output repeatability and a maximum lag error of 3.4%.[131] Zhang et al. reported a magnetic-mechanical-electrical (MME) core-sheath fiber fabricated using a coaxial printing method, enabling the construction of hybrid 2D/3D structures with magnetic activity and electrical conductivity, achieving integrated sensing and actuation functionality. The fiber exhibited programmable magnetic responsiveness, high electrical conductivity (2.07×10^6 S/m), and outstanding mechanical performance (150% strain limit and a Young's modulus of 0.87 MPa). In the 2D gripper structure integrated with MME coils, synchronized actuation and deformation sensing are enabled, allowing for real-time sensing of the gripped state while the gripper is actively engaging, thereby achieving bioinspired self-sensing.[132]

Soft actuators and sensors triggered by electric fields

Electrically driven actuation is a popular method in soft-robot actuation, which can be achieved by electroactive soft materials. This class of materials can produce deformation, luminescence, heat, or other physical changes under the action of electric fields or electrical signals.[133] These include non-ionic materials driven by an electric field or coulomb force, and they can be divided into electroactive polymers (EAPs), dielectric elastomers (DEs), shape-memory materials (SMMs), and other forms.

Electrical soft actuators based on ionic EAPs

Ionic EAP actuators represent a category of smart materials that respond to electrical stimuli by changing shape. They can produce large strains at relatively low voltages (1–5 V). The main categories of ionic EAPs include ionic polymer-metal composites (IPMCs), ionic gels, conducting polymers, and 1D/2D material-polymer composites. IPMCs typically consist of a thin ion-exchange membrane, such as Nafion or Flemion, sandwiched between two electrically conductive metal electrodes.[134] Similar to IPMCs, the electrically induced deformation of ionic gels is also caused by the heterogeneous distribution of ions inside the gel. The difference is that the polymer matrix of ionic gels, which can be polyelectrolytes, allows for the movement of both cations and anions contained in it.[50,135,136] In both IPMCs and ionic gels, the ion-movement-induced swelling is due to the combined effects of electrostatic interactions and osmotic pressure. Conductive polymers, on the other hand, operate through the doping/de-doping process.[51] When electrically stimulated, these polymers undergo a redox process that involves the insertion or expulsion of ions from the surrounding electrolyte to maintain charge neutrality, causing volumetric changes in the polymer. 1D materials such as CNTs[137] and 2D materials like molybdenum disulfide (MoS_2)[138] and MXenes[139] can also serve as flexible electrodes for sandwiching ionic polymer membranes, facilitating actuation by inducing deformation (e.g., expansion or contraction) under electrical stimuli. These materials have both superior mechanical and electrochemical properties. The manufacture of ionic EAP actuators can be integrated into microfabrication processes, enabling microactuators.[140,141] However, they are usually sensitive to common microfabrication chemicals and therefore are not compatible with standard silicon microfabrication processes, hindering mass production.

Dielectric elastomer actuators (DEAs)

DEAs are high-voltage electrically driven soft actuators.[142] They consist of a soft elastomeric membrane sandwiched between two compliant electrodes. When a high voltage establishes a strong electric field between the two electrodes, the electrostatic forces cause the elastomer to compress in thickness and induce motion. Due to DEAs having high energy density, fast response time, and lightweight nature, they are exploited to achieve fast crawling,[52] jumping,[143] jellyfish-like swimming,[144] undulatory underwater propulsion,[145] and snailfish-inspired propulsion in deep sea.[146] Conventional DEAs are subjected to the risk of irreversible dielectric breakdown of the intermediate dielectric layer. By replacing the solid dielectric membrane with a liquid dielectric, a hydraulically amplified self-healing electrostatic (HASEL) actuator is presented.[147,148] When actuated, the electrodes attracting each other push the liquid in between, redistributing the liquid and deforming the whole structure. Such an actuator integrates the strengths of both hydraulic and electrostatic actuators, achieving large strains and high strain rates. Apart from the electrostatic effect, charge electrohydrodynamics (EHD) is another principle that combines the strengths of electrical and hydraulic actuations.[149,150] The soft pumps developed based on this principle can inject electrons from the cathode into the dielectric fluid, such as Fluorinert FC-40 and Novec 7100, forming negatively charged ions. These ions are then accelerated by the electrophoretic force, moving toward the anode that discharges them. Such ion movement can induce a net flow inside the channel, finally producing the pumping effect. These soft pumps can be configured in planar shapes or fiber shapes, facilitating the development of compact and lightweight soft wearable devices without the need for bulky pumps and compressors. DEAs typically possess self-sensing capabilities. The change in the actuator's shape alters the capacitance, which can be used to estimate the actuator's deformation. The integrated sensing and actuation make them ideal for achieving environmental perception during bioinspired manipulation.[151]

Soft actuators based on electrothermal effects

The electrothermal effect is a phenomenon where heat is generated within a material through the application of electric current or electric field. This effect is widely used in the field of soft robotics to perform the desired deformation and movement by controlling a current flow. It is normally required to combine thermal-sensitive materials which have been discussed in section "thermal actuators and sensors" to develop soft robots based on electrothermal effect. SMAs, for example, can be produced in wires that can, in turn, be shaped in springs, which contract when heated electrically and can be used as actuators in soft robots. Combined with cable actuation, SMA springs have been used to implement the longitudinal-transverse arrangement of muscles in an octopus-like soft arm.[152,153] Wei et al. developed an inchworm-inspired soft robot with an optimized external SMA actuator configuration and a novel simplified constitutive model for improved performance and modeling accuracy. The electrical power source was applied to the SMA spring to induce joule heating, enabling contraction and driving the "bipedal" motion.[154] DeepStalk is a bioinspired soft robot designed for deep-sea exploration. Inspired by the eyestalks of deep-sea snails, DeepStalk utilizes SMA springs for actuation and a vector-PID (proportional-integral-derivative) controller for precise attitude control, enabling it to perform complex tasks under high hydrostatic pressure.[155] In another example, Kashef Tabrizian et al. integrated SMA wires into a self-healing polymer-based bending actuator for autonomous damage closure and healing in soft robotics.[156] The SMA wires simultaneously close large incisions, accelerate healing through joule heating, and reinforce the actuator for bending motion. In general, actuators built with SMAs can dramatically reduce the size, weight, and complexity of robotic systems. Their high force/weight ratio and large life cycle also favor the use of SMA-based actuators in soft robotics.[157] However, SMAs require high currents, and the transduction process is inefficient. In addition, the material activation is highly nonlinear and presents high hysteresis, making SMAs difficult to control accurately due to the many thermodynamic parameters that come into play. In addition to the discussion in section "thermal actuators based on liquid-crystal elastomers," LCE is a kind of smart material that deforms when heated; thus, it can also deform based on the electrothermal effect. Zadan et al. developed a driver that combined an LCE with a thin thermoelectric layer that was soft, stretchable, and compliant with the LCE deformation. The thermoelectric device layer consisted of *n*- and *p*-type bismuth telluride microcubes connected with a eutectic gallium-indium (EGaIn) liquid-metal interconnect and embedded in a 3D-printed elastomer matrix.[26] Zhang et al. designed an unbound electrothermal LCE actuator. It comprised an active LCE layer, a conductive LM-filled polyacrylic acid (LM-PA) layer, and a passive PI layer. A closed-conducting LM circuit and inductively coupled wireless power transfer (WPT) technology were used to realize the wireless drive. Conductive LM could provide the LCE soft actuators with strong electrothermal responsiveness and a self-sensing ability to sense their shape-deformation behavior.[158] An ultrafast and programmable soft actuator based on LCE and LM composite was introduced by Maurin et al. The composite was manufactured via direct-ink-writing technique with a sandwich structure, consisted of two LCE layers on the top and bottom sides, and one LM layer in the middle. The soft actuator was programming controlled by eddy-current induction heating, exhibiting a prompt response within milliseconds.[159]

Electroreceptors

Electrically responsive materials can also be utilized to develop electroreceptors. Inspired by earthworm synapses, Shim et al. developed a synaptic transistor composed of stretchable rubber. The synaptic transistor had properties similar to those of biological synapses in terms of the excitatory postsynaptic current (EPSC), paired pulse promotion (PPF), short-term memory (STM), long-term memory (LTM), and filters. An array of synaptic transistors was combined with pressure-sensitive rubber to create a deformable sensory skin. A soft neural robot was then developed. The surface of the robot was covered with sensory skin to perceive a tapped signal and change its motion state accordingly.[160] Kang et al. presented an ultrasensitive mechanical crack sensor inspired by the sensory system of a spider that was designed to detect tiny mechanical stresses and vibrations. The sensor adopted a microcrack structure and used changes in the cracks to sense small changes in the external force. It was made of flexible polymers and conductive nanomaterials with crack spacings of 10–50 nm. Experimental data showed that the sensor exhibited a sensitivity of up to 10^{-6} strain, a response time of less than 1 ms, and could detect pressure changes as low as 0.1 mPa[161]

Human skin, the body's largest organ, is a multi-layered structure comprising the epidermis, dermis, and subcutaneous tissue. It possesses high flexibility and durability, which enable it to adapt to various external environments. Primary functions of the skin include sensing touch, pain, and temperature changes. Receptors within the skin can precisely detect and respond to external stimuli, enabling humans to react promptly to their surroundings. Inspired by Merkle cells at the base of the epidermis and Ruffini endings in the dermis of human skin, Liu et al. developed electronic skin with a 3D architecture. At a physical level, it realized synchronous and decoupling sensing of various mechanical signals such as pressure, shear force, and strain. The force-sensing unit was designed using an eight-arm cage structure and was highly sensitive to external forces. The strain sensor was located on the arched structure at the bottom of the device, was sensitive only to the tensile strain inside the surface, and was barely disturbed by pressure. Based on spatiotemporal mapping, the 3DAE-Skin tactile system could be used to distinguish surfaces with different roughness values. Moreover, the elastic modulus and local curvature of an object could be predicted simultaneously. Consequently, experiments were conducted to verify if the electronic skin could detect different food shapes, such as fruits and bread.[162]

Soft actuators and sensors triggered by chemical reactions

Chemical reactions can be used to trigger the actuation and sensing of soft robots. Unlike traditional soft robots relying on external stimuli such as electrical, thermal, or pneumatic input, chemically triggered soft robots gain energy from reactions like pH changes, solvent variation, combustion, or enzymatic activity.

pH-responsive soft actuators

Chemical-driven actuators can be used in situations where adaptive motion in response to environmental stimuli is required. Various chemical-driven soft actuators based on different actuation mechanisms have been developed. pH-responsive actuators, typically made of hydrogels with ionizable groups, can undergo structural changes like expansion or contraction based on the surrounding pH levels. For instance, hydrogel actuators composed of polyacrylic acid (PAAc) can expand or contract as the ionization of its carboxyl groups varies with pH.[163] The degree of swelling of the hydrogel actuators composed of poly(2-(dimethylamino) ethyl methacrylate) (PDMAEMA) can be controlled by the protonation of its amino groups.[164] Peng et al. fabricated a hydrogel with a double-curved structure. By stimulating the hydrogel with an acetone solution, the structure transitioned from being concave to being convex and expanded to cause the robot to jump.[165] Wang et al. prepared asymmetric hydrogel structures by direct femtosecond laser writing. Micrometer-scale hydrogels could rapidly respond to changes in pH, controlling the capture and release of tiny particles; moreover, adjusting the pH enabled the structure to undergo anisotropic expansion.[54] In biomedicine, pH-responsive actuators could be used for targeted drug-delivery systems that release medication in response to pH changes in different parts of the GI tract.[166]

Combustion-driven soft actuators

Combustion-driven soft actuators utilize chemical energy from fuels as their power source. By leveraging the gases generated from fuel decomposition, these robots achieve actuation either through expansion of the soft structures or jet propulsion, enabling their movement. Bartlett et al. designed a multi-material 3D-printed soft robot where the combustion of butane and oxygen causes gas volume expansion, propelling the robot into the air.[56] Wehner et al. utilized microfluidic logic as a soft controller and employed a multi-material embedded 3D printing method to fabricate a soft robot. By using platinum as a catalyst to control the reaction of hydrogen peroxide solution, gas was generated, causing asymmetric expansion of the robot, which in turn resulted in displacement.[167] Yang et al. utilized NiTi-Pt to enable controlled catalytic combustion of various fuels, driving an 88-mg autonomous crawling robot. Experiments were conducted to evaluate its motion in different environments and its load-carrying capabilities.[168] Aubin et al. developed a quadrupedal insect-scale robot that eliminated the need for valves by employing a passive quenching mechanism. The combustion of methane generated gas capable of producing pulsed thrust greater than 9 N.[7]

Solvent-responsive soft actuators

Solvent-responsive soft actuators selectively adsorb volatile chemical solvents, such as acetone, ethanol, and tetrahydrofuran. The volatile solvents alter the internal structure of the material, inducing deformation to achieve actuation.[169] Zhang et al. developed two highly elastic polymer actuator materials, polyvinylidene fluoride (PVDF) and PVA, capable of rapid response to acetone vapor. Microchannel structures were fabricated on the bilayer polymer material, enabling reversible and fatigue-free curling.[170] Mu et al. utilized the absorption/desorption of polar vapors (alcohol and acetone) in the intrinsic nano-scale molecular channels of perfluorosulfonic acid ionomer (PFSA) films to induce deformation and drive actuation. By designing patterns on PET films, they achieved 2D roll and 3D helical structures.[171]

Chemoreceptors

Organisms react to environmental changes by detecting chemical indicators in their environment. They adjust their behavior, growth, and reproductive strategies based on changes in pollutant levels, pH, and other factors. Qu et al. described the design and performance of a bionic flexible volatile organic compound (VOC) sensor based on dynamic surface folds and a two-signal response. The sensor realized sensitive detection of VOCs by simulating the dynamic folding behavior of biological structures in nature. Comprising flexible substrate materials and surface nanostructures, the sensor exhibited high sensitivity to VOCs through physical and electrochemical changes upon exposure to VOCs.[172] Inspired by the folded sensory epithelium of rhinophores, Wang et al. developed a stretchable electrochemical sensor. The glucose concentration was sensed by covering the elastic fibers with gold nanofilms that could be folded. The sensitivity of the sensor was 195.4 $\mu A \cdot mM$ under 150% strain with a low glucose concentration in the range 8–206 μM. The sensitivity was 14.2 $\mu A \cdot mM$ under 0% strain with a high glucose concentration in the range 10–100 mM. Changes in the sensor length altered the signal strength, and this change in signal strength could be used to distinguish the direction of the molecular source.[173] Ion exchange or ionic absorption/desorption can induce changes in volume or electrical resistance. Base on this method, a soft-foldable robot was developed using polytetrafluoroethylene (PTFE) films driven by an ionic liquid composed of a mixture of sodium chloride and deionized water. Simultaneously, the ionic liquid was utilized for sensing, where an ionic resistive sensor detected resistance changes induced by volume variations of the liquid within the module, enabling real-time state monitoring of the robot. The fabricated bioinspired self-sensing soft-rigid hybrid continuum robot features real-time shape-sensing capabilities, enabling it to grasp and place objects of varying hardness, shape, and weight. Additionally, it has been applied to medical scenarios, achieving functions such as puncturing and laser ablation.[174]

Soft actuators and sensors triggered by mechanical forces

Mechanical-driven soft robots represent a combination of traditional mechanical engineering and advanced materials science. The soft robots can utilize various mechanisms, such as cables, pulleys, pneumatic systems, and hydraulic systems, to achieve controllable motions.[18] The soft robots developed based on mechanical driving systems can overcome the shortages of flexibility and adaptability that traditional mechanically driven rigid robots have.[175]

Cable-driven soft actuators

The use of tendon systems as drivers has been popular. Several cable-driven bionic robots have been developed for this purpose. They are usually driven by motor-driven cables, with a slender cable separating the driver from the robot body such that the size of the robots can be further reduced.[176,177] Kim et al. introduced a soft spherical tensegrity robot applying the dynamic relaxation technique. The robot consists of six rods and 24 cables, whose geometry resembles Jessen's orthogonal icosahedron, and thus it is able to realize rolling locomotion through the structure's deformation.[178] A special zigzag cable routing (ZCR) mode was presented by a cable-driven soft actuator to improve the helical motion. The ZCR actuator shows advantages in motion smoothness, low energy consumption, and designability.[179] Based on soft silicon materials, a four-cable-driven soft arm was designed to operate in an underwater environment. In order to achieve steady-state and dynamic responses under the water, a dynamic model based on Kane's method was proposed. Hydrodynamics was considered for this model and serves as the foundation for the soft arm being used in the special environments.[180] It is popular to use a cable-driven soft actuator for surgical purposes. A cable-driven soft manipulator that was designed for performing more precise laparoscopic radical prostatectomy (RARP) was introduced by Ru et al. This soft manipulator has a diameter of 10 mm and was manufactured by the casting method. Three embedded cables enable the soft manipulator to reach the maximum bending angle of 270°, showing good flexibility and dexterity.[181]

Fluid-driven soft actuators

Fluid-driven soft actuators operate by harnessing fluid pressure to deform flexible, elastomeric structures. Typically constructed from soft materials like silicone rubber, these actuators feature specially designed internal chambers with intricate patterns that expand or contract when fluids (liquids or gases) are pumped in or out.[58,182] This induces heterogeneous stress distribution, leading to overall structural deformation. The deformation characteristics are further enhanced by incorporating constraints such as fiber reinforcements,[183,184] constraint layers,[185,186] and heterogeneous materials,[56] which guide or limit expansion in specific directions. Fluid-driven actuators can achieve various movement modes, including bending, twisting, elongation, or combinations thereof.[183] The amplitude and speed of motion can be finely controlled through precise regulation of fluid pressure and volume, enabling highly tuned movements. Sanchez et al. introduced a 3D knitting-based approach as a sustainable, waste-free method to produce a pneumatic soft robot with customizable mechanical properties. By tailoring knit architectures and materials, it enables the monolithic and recyclable design of pneumatic soft robots.[187] A pneumatic approach could also be used to produce logic gates to control smartly for soft-robotic actuators. In one study, a soft actuator was designed with the 3D-printed pneumatic logic gates (PLGs) to perform Boolean operations (AND, OR, NOT) to eliminate the need for rigid components like conventional valves and circuits. The soft actuator was fully additively manufactured, enabling rapid and sustainable fabrication. This technique was tested on a soft-robotic walker to demonstrate the versatility, durability, and potential for integrating with various systems.[188] Furthermore, the biomechanics of spiders can inspire the development of advanced fluidic soft actuators for robotics. A thermoplastic polyurethane-based rotary semi-fluidic actuator was developed based on the investigation of the unique folding mechanism of the articular membrane in jumping spider leg joints. As a result, the actuator is capable of achieving a working angle over 120° with high torques.[189] In addition, Smith et al. developed a fully 3D-printed micro-hydraulic system for tiny soft robotics. The microscale soft robot was designed based on the inspiration of spiders and produced by two-photon polymerization (2PP) printing technology. This design mimics the hemolymph-driven motion of the spider joint and uses high-modulus polymers to create a compliant and sealed structure for hydraulic fluid that enables the soft robot to achieve unprecedented force and displacement efficiency.[190]

Mechanoreceptors

Hierarchies inspired by gecko-foot hair have recently been introduced into tactile sensors to achieve high sensitivity, rapid response, and good durability. For example, piezoelectric tactile sensors based on interlocking and layered microcolumns coated with nanowires exhibit high sensitivity and rapid response.[191] Inspired by natural biological ion channels, Lin et al. prepared an artificial ion channel composed of a polymer, electrolyte, and nanopore membrane to provide a dynamic current response to various external forces. The ion-channel pressure sensor had a sensitivity of approximately 5.6 kPa^{-1} and a response time of approximately 12 ms at a frequency of 1 Hz. Such ion-channel pressure sensors could detect complex movements such as pressing and folding.[192] Calderon et al. mimicked the mechanosensory abilities of earthworm skin using sensors that measured the strain and pressure from deformable microchannels filled with electrically conductive liquid-metal eutectic alloys. The resolution and accuracy of the artificial skin could be improved by adding a thinly patterned silicone layer to the outer surface.[193] Harada et al. produced printed, multifunctional, and highly sensitive electronic whisker arrays that surpassed real whiskers in function; they developed their strain sensor using CNT-Ag-NP thin films. When high strain was applied to the film, the entangled CNTs changed the distance between the AgNPs, which was related to the resistance; hence, the strain was determined by measuring the resistance.[194]

Biohybrid actuators

Biohybrid actuators integrate biological tissues with artificial components to create functional devices capable of movement. These actuators can be broadly categorized into two types: non-scalable actuators and scalable actuators.[195] The first category includes systems that utilize fully integrated biological systems, such as motile bacteria[196–198] or explanted whole-muscle tissues,[199,200] for different applications at micro and macro scales. The second category involves the use of engineered cells, such as cardiomyocytes and skeletal muscle cells, assembled to create scalable devices capable of diverse applications including robot locomotion,[61,201,202] pumping,[203] and micromanipulation.[204] Biohybrid actuators leverage the unique properties of living tissues, such as self-healing, adaptability, and the use of biodegradable fuel, to achieve functionalities that are difficult to replicate with synthetic materials alone. For example, muscle tissues can dynamically respond to environmental changes and modulate stiffness, which is crucial for developing compliant robots with inherent control over mechanical impedance. Using microorganisms with taxis behavior to drive microrobots can guide the robot to the targeted location autonomously without external interventions.

Cardiomyocytes and skeletal muscle cells are commonly used as biological hybrid actuators. Park et al. combined cells with an artificial fish skeleton made of gold and flexible materials to create a bionic fish. Cardiac muscle cells from rats were genetically engineered that could be stimulated by light. The bionic fish could then swim by modulating the light.[202] Li et al. developed a valveless pump using skeletal muscle cells. It was driven by winding muscle rings around a soft hydrogel tube. Electrical stimulation of muscle-ring contraction produced elastic waves that propagated along the hose, establishing a time-averaged pressure gradient to produce a net flow.[205] Guix et al. combined a 3D-printed, flexible, snake-bone spring skeleton with skeletal muscle cells to create a swimming biohybrid robot. Muscle rings surrounded the outside of the spring skeleton and controlled the contractions to achieve movement.[61] Cao et al. produced a hybrid variable-stiffness actuator. PPy was combined with an alginate (Alg) hydrogel and the gel layer was mineralized with cell-derived plasma membrane nanofragments (PMNFs). Changes in the actuator stiffness could be achieved by growing bone.[206] Tetsuka et al. developed a cordless, lightweight biohybrid soft robot. The cardiomyocytes were arranged on a 3D-printed multi-material scaffold inspired by the accordion structure; 9-V pulse signals were generated by wireless bioelectronics technology to stimulate the cells and control the speed and direction of the robot movement.[207] Herr et al. used frog semitendon muscles to power a swimming soft robot. The tendons were stitched to a silicone tail enabling the robot to swim using open-loop stimulation by means of electrical pulses. It could start, stop, and turn. Moreover, life support of the frog muscles could be realized using broad-spectrum antibiotic solutions.[199] Kinjo et al. developed a biohybrid bipedal robot that consists of a float for maintaining an upright posture in cultured medium, two flexible PDMS substrates, 3D printed legs, and cultured skeletal muscle tissues. The electrical stimulus enables this bipedal robot to perform multiple types of movements, including moving forward, stopping, and turning by alternating muscle contraction in the left and right legs.[208] Integrated with living skeletal muscle with synthetic components, a biohybrid swimming robot was developed. The muscle tissue was cultured by a cell-laden hydrogel, which comprises fibrinogen, thrombin, and Matrigel. It was subsequently combined with the hydrogel and assembled around the 3D-printed serpentine spring skeleton. This biohybrid robot can perform directional swimming in the liquid medium and achieve coasting motion near to the bottom surface.[61] Martel et al. combined flagellar nanomotors with nano-scale magnetotactic bacteria to create a robotic driver with propulsion and steering capabilities. They proposed a method for image tracking and closed-loop control of a robot using a magnetic resonance imaging (MRI) system.[209]

However, the biohybrid actuators still face challenges such as limited long-term stability, ethical issues related to cell sourcing, and difficulties in maintaining cell viability and function over extended periods. Biohybrid actuators currently underperform compared to some artificial actuators in terms of stress, stroke, and robustness, and substantial research is needed to optimize their performance and scalability for broader use.

Material stability and biocompatibility in soft robotics

Stability

The long-term stability and degradation of materials are pivotal concerns in soft robotics, particularly when contrasted with traditional rigid systems. Due to their flexibility, soft-robotic materials, such as elastomers, hydrogels, and SMPs, are inherently susceptible to fatigue, wear, and environmental degradation. Mechanical stresses, temperature fluctuations, humidity, and exposure to various chemical environments exacerbate these issues, causing changes in mechanical properties that compromise performance and reliability over time. Studies have shown that environmental factors, such as UV radiation, can accelerate the degradation of soft materials, leading to microcracking and loss of elasticity.[210]

Maintaining material stability becomes even more critical in biohybrid robots, which integrate living cells or tissues with synthetic materials. Degradation byproducts can release toxic substances or cause adverse biochemical reactions, threatening the viability of biological components and the overall system's functionality.[211] Researchers are developing innovative materials that combine enhanced durability with biocompatibility to mitigate these challenges. For example, PDMS is extensively used for its chemical stability and biocompatibility, while advances in polymer science have produced thermoplastic polyurethanes and elastomeric composites with superior mechanical strength and resistance to degradation.[212]

Biocompatibility and safety

Ensuring biocompatibility and safety is paramount in biohybrid soft robotics, especially for human or animal applications. Materials used must meet stringent criteria: they should be non-toxic, non-immunogenic, and must not induce inflammatory responses. Furthermore, these materials should facilitate cellular processes such as attachment, proliferation, and metabolic function without interference.

Rigorous biocompatibility testing is critical, employing cytotoxicity assays, hemocompatibility evaluations, and *in vivo* implantation studies to monitor immune responses and tissue integration. Hydrogels such as alginate and gelatin methacrylate (GelMA) have emerged as leading candidates due to their ability to mimic the extracellular matrix (ECM), thereby creating a conducive environment for cell encapsulation and growth.[213] Such materials support critical processes in biohybrid systems while minimizing the risk of adverse cellular responses.

Efforts to ensure the safe deployment of biohybrid soft robots include the following strategies:

(1) Material encapsulation: encapsulating electronic and actuation components prevents direct interaction with biological tissues, minimizing risks of inflammatory or immunogenic reactions.[214]
(2) Sterilization techniques: researchers are developing materials compatible with sterilization methods like gamma irradiation or ethylene oxide treatment. For instance, studies indicate that incorporating cross-linking agents into hydrogels can preserve their structural integrity post sterilization.[60]
(3) Degradation control: engineering biodegradable materials with controlled degradation rates aligned with device lifespans ensures that degradation byproducts are safely resorbed or excreted. Such innovations are vital for implants and wearable biohybrid systems.[211]

Scaling biohybrid systems for clinical applications presents multifaceted challenges, including maintaining consistent quality and performance. Regulatory frameworks, such as those by the US Food and Drug Administration (FDA) and European Medicines Agency (EMA), demand rigorous validation of materials and devices, often necessitating time-intensive and expensive testing protocols. Furthermore, standardizing testing protocols across interdisciplinary domains remains an ongoing challenge. Collaborative efforts between materials scientists, biologists, and clinicians are essential to streamline these processes. Focused research into developing adaptive, dynamic materials that align with regulatory standards will pave the way for safe and effective biohybrid soft-robotics clinical integration.[215]

ANIMAL-INSPIRED SOFT ROBOTS

Soft robotics has been looking at nature for inspiration from animals since the beginning. In nature, the skeleton of animals includes three types of skeleton—namely, the exoskeleton, endoskeleton, and hydroskeleton. The exoskeleton is an external skeleton that supports the body shape and protects the internal organs. Examples include crab shells and insect cuticles. An endoskeleton supports the body. Most vertebrates have endoskeletons, which include cartilage and hard bones.[216,217] This skeletal system grows with the body supporting it as the animal develops in size; consequently, vertebrates can grow larger than invertebrates. In general, there are two types of endoskeletons in porous animals—that is, spicules and spongin endoskeletons. They are scattered within the mesoglea or protrude from the body surface. The endoskeletons of echinoderms are composed of calcium carbonate and protein, the crystals of these chemicals being arranged in the same direction. Conversely, the hydroskeleton is a skeleton supported by hydrostatic fluid pressure and is the primary skeletal form in invertebrates.[218] As soft tissues driven by a hydrostatic skeleton cannot exert large inertial forces or attain rapid speeds when bearing weight, animals with hydroskeletons are often limited in size.

Figure 3 provides a comprehensive overview of the biological classification of the animal system. We selectively analyzed the typical bio-models under different animal types and illustrated the development trends of soft robots based on these bio-models by using four key metrics: research density, research impact, application potential, and technology maturity. These trends are visually displayed by the relative height of the colored bar, which provides a clear demonstration of how each bio-model ranks across these dimensions. We believe these trends could provide a unique perspective for researchers and serve as a guide for future research in bioinspired soft-robotics. The data for this analysis were collected from the Web of Science (WOS) and Google Patent databases. It is worth noting that the trends shown in the figures (including Figures 3, 5, and 7) provide only a relative reference and should not be interpreted as precise data. This approach helps to identify areas with high potential for innovation and application.

Vertebrates

Pisces-inspired soft robots

Fish inhabit nearly all aquatic environments. After long-term biological evolution, fish exhibit high movement efficiency, environmental adaptability, and multiple functions. Many underwater bionic robots have emerged inspired by fish propulsion methods. Based on the morphological function of fish, Webb proposed two classification methods premised on propulsive organs, called body caudal fin (BCF) propulsion and median paired-fin propulsion.[219] For example, batoid fish can perform delicate maneuvers and rotations by independently and asymmetrically actuating their pectoral fins. Their pectoral fins are composed primarily of three components, namely cartilage, double-layered muscles, and other organic tissues. The Webb soft robot was designed based on this structure; it used two layers of soft silicone rubber as a base, sandwiching an energy-storage skeleton made of gold, which was then wrapped by rat cardiomyocytes with fibronectin. The cell movement was activated by light stimulation, enabling the robot to move along a designated route (Figure 4A).[202] A lamprey-like robot was developed that used force plates on the left and right sides of each segment to sense the hydrodynamic forces. It could obtain sensory feedback from water to coordinate its movement if the central control system was damaged. Using a combination of central and peripheral components, the robot could resist more neural interference and maintain high-speed swimming movements.[220]

Deep-sea ecosystems are among the least-explored areas on Earth. Consequently, in-depth research could yield new biological discoveries. For instance, deep-sea organisms exhibit

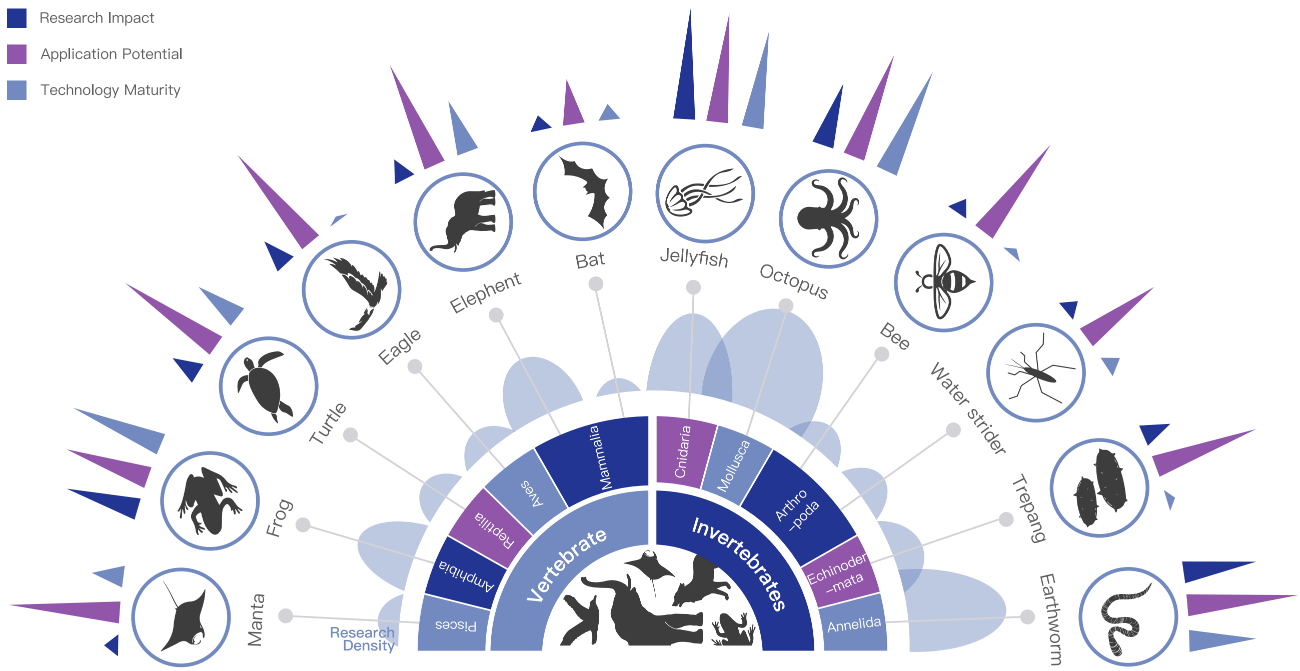

Figure 3. The distribution of animal models used in soft-robotics research in recent years, among which different types of skeletons, including exoskeletons, endoskeletons, and hydroskeletons, have been used in the design of soft and bioinspired/biohybrid robots

Here, the area under each animal model in the middle ring indicates the research density of a given animal model in the current soft-robotics field, whereas the graph bars of the outer ring indicate the research impact, application potential, and technology maturity involved in using a particular animal model for the design of soft robots.

remarkably low metabolic rates, extended lifespans, and structures that can withstand high pressures. Robots designed specifically for deep-sea exploration could be developed by studying deep-sea organisms.[225] Inspired by the structure of deep-sea snailfish, Li et al. developed an untethered soft robot for deep-sea exploration (Figure 4B). The robot was equipped with onboard power control and a pressure-protected actuation unit. The robot swam using the swinging motion of the dielectric elastomer fins.[146] To explore high-frequency swimming motion, Zhu et al. designed a new platform inspired by the yellowfin tuna (*Thunnus albacares*) and Atlantic mackerel (*Scomber scombrus*). They analyzed the fishes' body kinematics, speed, and power with increasing tail beat frequencies to quantify their swimming performance. A Tunabot of length 255 mm was developed, achieving a maximum tail-beat frequency of 15 Hz, corresponding to a swimming speed of 4.0 body lengths/s. As the frequency increased, the cost of transport (COT) exhibited a fish-like U-shaped response, shedding light on the development of fish-like robots for underwater exploration.[226] Inspired by mudskippers, Lin et al. developed an amphibious robot by combining BCF propulsion and legged locomotion on land to achieve amphibious movement. The robot was driven by a pair of 2-degree-of-freedom (DOF) pectoral fins and a single-DOF caudal fin, which improved its efficiency and agility. The terrestrial and aquatic turning speeds of the robot improved by 50.1% and 24.4%, respectively, because of the intrinsic coordination of the pectoral and caudal fins.[227] By imitating the adhesion mechanism of the dorsal fin of rays (infraclass Batoidea), Wang et al. fabricated a disk-like structure using multi-material 3D printing (with stiffness spanning three orders of magnitude) for a bioinspired soft swimming robot. Carbon-fiber spines were fabricated to a base of diameter 270 μm and attached to the soft actuator-controlled gill plates to mimic their function. The bionic prototype could attach to different surfaces and generate considerable detachment forces, up to 340 times the weight of the disk-shaped prototype, producing considerably enhanced friction on substrates of varying roughness. The resulting bionic robot could attach to and ride on a variety of surfaces, including shark skin.[228]

Another example is the work of Katzschmann et al., who developed a hydraulically driven soft-robotic fish propelled by a soft tail comprising two fluid chambers. Water circulation through the internal lumen was used as the driving fluid to control the caudal fin propulsion and yaw movement. Complex curved cavities were fabricated through wax molding and casting processes, enabling a wide range of shapes. Additionally, dynamic diving capabilities were introduced, using the pectoral fin as a diving plane, to achieve movements similar to those of fish in water.[229] Inspired by the undulating fan wings of lionfish gliding in coral reefs, Aubin et al. used liquid electrolytes to provide electrical power and hydraulic drive for soft robots. A replica mold was used to create the silicone shell of the robot, within which internal channels for fluid actuation and larger cavities were embedded to house the pump and control hardware. Two independent pumps were housed inside the robot, with fluid circulating between the reservoirs and actuators. The fluid

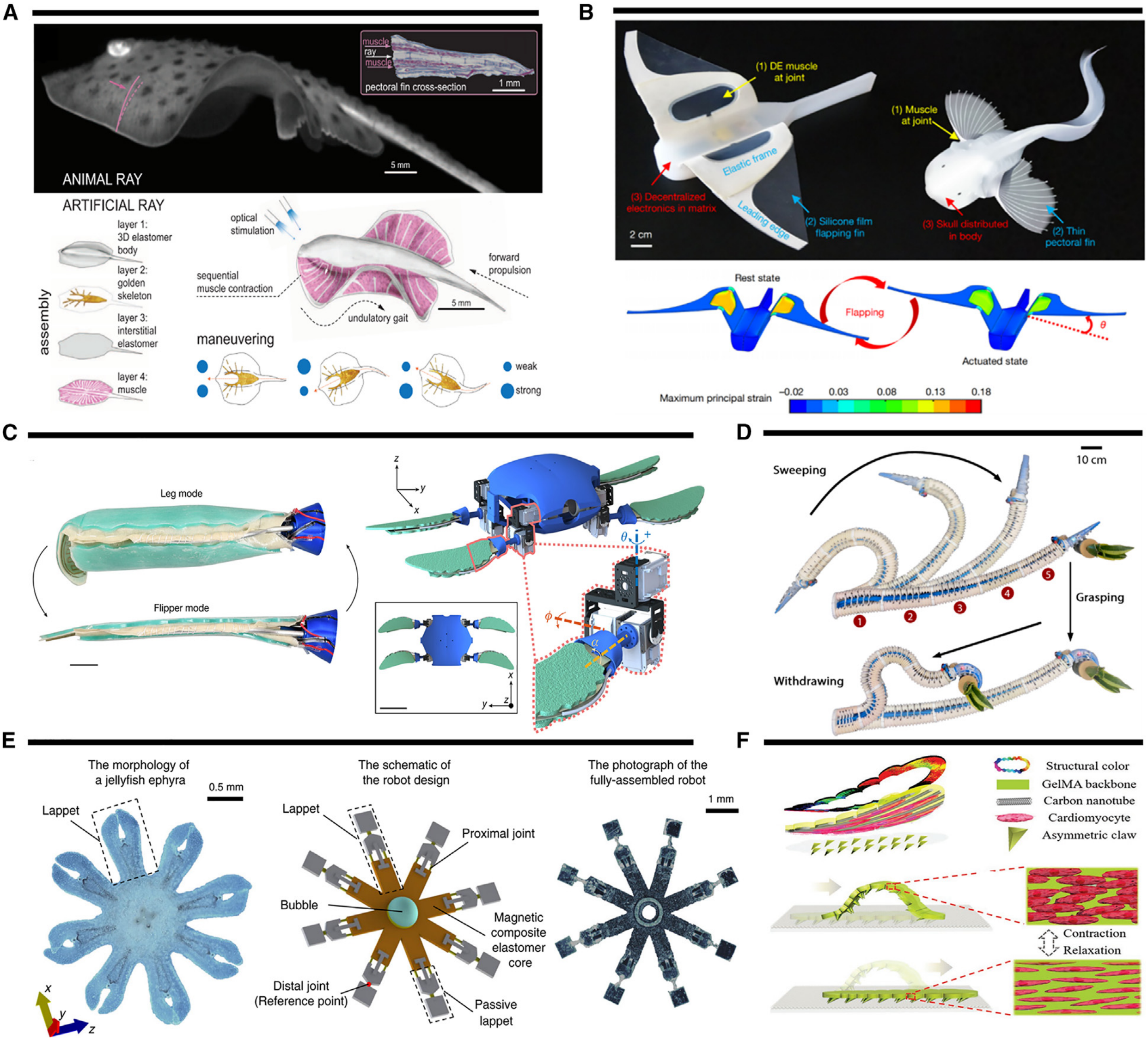

Figure 4. Soft robots developed with inspiration by animal models

(A) Artificial ray possesses a sequential muscle structure similar to that of an animal ray, with propulsion and maneuvering controlled by optical stimulation. Reprinted with permission from Park et al.[202] Copyright 2016, AAAS.

(B) Snailfish-inspired soft robot designed and fabricated based on DE muscle. Reprinted with permission from Li et al.[146] Copyright 2021, Springer Nature.

(C) Turtle-inspired amphibious robot. Reprinted with permission from Baines et al.[221] Copyright 2022, Springer Nature.

(D) Octopus-inspired soft robot exhibits sweeping, grasping, and withdrawing motions. Reprinted with permission from Xie et al.[222] Copyright 2023, AAAS.

(E) Schematic design of a soft millirobot mimics the morphology of a jellyfish ephyra. Reprinted with permission from Ren et al.[223] Copyright 2019, Springer Nature.

(F) Schematic illustration of the caterpillar-inspired soft robot consisting of three layers, with crawling motion actuated by cardiomyocytes. Reprinted with permission from Sun et al.[224] Copyright 2020, Wiley-VCH.

from the back was pumped into the pectoral fins to create thrust, and the fluid in the tail circulated on both sides to generate thrust from the tail fins. Experiments showed that the robot was able to swim against a current at a speed of more than 1.5 body lengths/min with a theoretical maximum endurance of more than 36 h.[230]

Amphibian-inspired soft robots

In nature, an animal's form is usually best suited for land or aquatic movement, but not for both. However, amphibians can move in both environments. Extensive research has been conducted on the construction of amphibian-inspired robots. Robots can be classified into two categories. The first category includes those with multiple physically independent propulsion mechanisms, such as propellers and wheels, for movement in water and on land. The second category includes robots that use a unified propulsion mechanism to move in both media, involving hybrid paddle legs or an undulating body.

Consequently, Li et al. developed force models for arbitrarily shaped legs and bodies that moved freely in granular media. This model could be used to predict robot motion in granular media with various leg shapes and stride frequencies. The study provided a reference for the movement of amphibian robots in alternating water and land environments.[231] Salamanders swim in water by undulating their bodies and legs while utilizing their tails. Crespi et al. developed a bionic amphibious robot that mimicked the swimming and walking patterns of salamanders. The robot was approximately 90 cm long, weighed approximately 2.5 kg, and comprised multiple modules, each approximately 7.5 cm long, containing joints with 2 DOF. The robot was capable of walking at 0.4 m/s on land and swimming at 0.2 m/s. The onboard multi-sensor system, including accelerometers, gyroscopes, and underwater sonar, could monitor the motion status and environmental information in real time.[232] Horvat et al. developed an amphibious high-redundancy robot capable of locomotion in shallow water. They designed a bioinspired control framework to coordinate the movements of the spine and limbs and studied the effects of the presence and absence of a tail on its locomotion performance.[233] Amphibians such as frogs use webbed feet for swimming gaits in water and employ quadrupedal jumping for locomotion on land. Tang et al. developed a bionic frog swimming robot based on DEAs, mimicking frog legs and webbed feet. The body was made of 3D-printed polylactide material, and the total mass of the two DEAs was 14 g, which was only 13% of its total mass. The average swimming speed of the robot was 19 mm/s[234] In another study, Fan et al. introduced a frog-inspired swimming soft robot. The forelimb was simplified into a single-DOF link comprising an elbow joint and forelimb flipper; the hindlimb was simplified into a 3-DOF planar connection mechanism driven by an articulated pneumatic soft actuator. The overall size was 0.175 × 0.100 × 0.060 m, the average propulsion speed during linear motion was 0.075 m/s, and the average turning speed was 15°/s.[235]

Reptilia-inspired soft robots

Reptilia is a large and diverse group in the vertebrate animal world, and it contains some typical species, such as snakes, lizards, turtles, and crocodiles. These creatures exhibit efficient locomotion and unique structural mechanisms, offering innovative inspiration for the development of soft robots. Figure 4C illustrates a soft robot inspired by the streamlined fins of sea turtles and the columnar legs and gait of tortoises. The designers integrated traditional rigid components and soft materials to adapt to multi-environmental movements by changing the shape and gait of the limbs. The body comprised four subsystems, namely the chassis, shell, shoulder joints, and deformable limbs. The chassis housed the electronic components. The shell provided ballast space for buoyancy adjustment, streamlining, payload storage, and protection. Three motors were mounted on each shoulder joint to enable a wide range of gaits. The deformable limb comprised heat-activated materials and inflated pneumatic push rods, which allowed changes in the cross-sectional area and stiffness of the limb.[221] Moreover, Garrad et al. proposed the concept of a soft-matter computer (SMC) inspired by the manner in which information was encoded and transmitted in the vascular system. The SMC used only flexible materials, which solved the problem of poor robot flexibility caused by traditional robot control systems made of hard materials such as silicon. Conductive fluid receptors (CFRs) were the building blocks of the SMC. The CFRs comprised two electrodes placed on either side of a hose, parallel to the direction of fluid flow, ultimately producing a binary signal that could be calculated. The SMCs were subsequently embedded in bionic gecko robots.[236]

A major advantage of soft-robotic terrestrial locomotion is its ability to exploit inherent compliance to traverse irregular surfaces. Inspired by the movement of serpent-like organisms, Onal et al. constructed a snakelike soft robot with a fluid chamber driven by air to produce a wavy motion. The robot was 30 cm long and 5 cm in diameter and had 12 segmented chambers, each capable of producing bending angles of up to 30°. By precisely controlling the pressure in each chamber, the robot could achieve velocities of up to 5 cm/s. The system operated in a pressure range of 0.1–0.5 MPa; the response time of each segment was less than 200 ms, enabling smooth and continuous movement.[237] Qi et al. developed a multi-material 3D-printed snakeskin that enabled soft snake robots to glide in waves on rough surfaces. The snake skin comprised a soft skin base and rigid scales. The biomimetic design of the shape and arrangement of the scales effectively generated various types of anisotropic friction and provided a method to switch the direction of the robot's movement in the same or opposite direction as the propagation direction of the traveling wave fluctuations. The snake body comprised soft pneumatic bending actuators containing independent air chambers to produce wavelike bending deformations. When the amplitude of the pressure input was 172 kPa (25 psi), the snakelike motion of the robot reached 37 mm/s.[238]

Moreover, Sangbae et al. developed a climbing robot that used directional adhesion technology to achieve efficient climbing on smooth vertical surfaces. The robot was made of a microstructure adhesion material and modeled after the microstructure of the gecko foot; it exhibited excellent adhesion and desorption performance. The robot weighed approximately 1.2 kg and was 30 cm long, 15 cm wide, and 10 cm high. With an adhesion of up to 20 N/cm^2, it could support its own weight and carry additional loads. The robot was equipped with sensors (such as force sensors and accelerometers) to monitor its state of adhesion and movement in real time. The robot could move up to 5 cm/s on a vertical surface.[239]

Aves-inspired soft robots

Compared to traditional man-made aircraft, birds can use mechanical structures and biological materials to dynamically change their shape and adapt to different flight environments. Consequently, researchers have studied bionic models of bird deformation, flight, perching, mid-air grabbing, and dynamic pursuit. Roderick et al. developed a bird-inspired robot that could dynamically perch on complex surfaces and grab irregular objects. It was inspired by the way birds take off, land, and grab. By integrating this mechanism into the robot's two legs, which could work together to grab a perch when landing, balance to stabilize itself, and safely take off, the robot's legs passively converted the impact energy into a grasping force. The robot legs were 3D-printed structures, whereas the "muscles" and "tendons" were motors and fishing lines, respectively. The robot had a powerful clutch that could trigger closure within 20 ms. Posture was detected using an accelerometer. The underactuated gripper could wrap around irregularly shaped objects in 50 ms.[240]

Furthermore, Chang et al. developed a method to create a feathered, biological-mechanical hybrid robot that could change its wing shape. A flying robot was combined with actual pigeon feathers, which were connected through artificial "elastic ligaments" and "wing joints." It weighed 280 g, and its wingspan was 80 cm. The positions of the 40 elastically connected feathers were controlled using four servo-driven wrist and finger joints. They studied the interaction between the individual feathers of various birds and discovered two main mechanical mechanisms behind the deformation of bird wings, namely the passive redistribution of feathers and the movement of adjacent and overlapping feathers through feather roots. A small hook-like joint held them together. By controlling the mechanical joints that caused the wings to move asymmetrically, the pigeon robot could perform stable turning actions within a small radius.[241] In addition, Chin et al. developed a low-loss transmission system that mimicked the acrobatic movements of birds with flexible nylon hinges and double bearings that suppressed flap sway and stored elasticity. It could hover, perform high-speed darts, and perform aerobic turns while climbing. The optimized motor drive mode enabled the flapping wing to operate at approximately 15 Hz and generate 40 g of thrust, exceeding its own weight.[242]

Mammalia-inspired soft robots

Great potential can be found in Mammalia-inspired soft robots. By mimicking the muscle structures, joint articulation, and actuation principles of mammals, sophisticated soft robots capable of performing complex tasks such as grasping, walking, swimming, and running can be developed. Ramezani et al. modeled the morphological characteristics of bat wings to create a 93-g autonomous flying robot. A high-speed camera was used to record the bat's trajectory as it flew. Using principal-component analysis, several key DOF were selected from more than 40 DOF of the bat wing to realize the movement of the wing skeleton. An anisotropic 56-μm-thin silicon-based film was prepared and coated on the robot skeleton. The control method was designed to realize zero-path, banking, and diving modes.[243]

Inspired by the curvature of the cheetah's spine during running, Tang et al. designed a new spring-driven flexible robot with a bistable spine. The robot had two stable states that could be controlled by inputting compressed air into a pipe in the robot. Achieving a rapid conversion between these two stable states could release a large amount of energy, enabling the robot to quickly exert force on the ground and achieve high speeds. The robot was approximately 7 cm long and weighed 45 g. It could move at a speed of 2.68 body lengths/s.[244] Another study presents a pangolin-inspired untethered magnetic robot designed for on-demand biomedical heating applications. The robot has a bilayer structure, integrating soft materials with rigid metallic components and applying an external radio-frequency (RF) field to induce joule heating, which can achieve localized heating above 70°C at distances greater than 5 cm within 30 s. It showed advanced capabilities including cargo release and treatments for hyperthermia and bleeding mitigation.[245]

As a member of the mammalian class, human beings have sophisticated biological morphology and body structure, which inspired the development of biomimetic soft robotics. Human mimetic humanoids have been designed based on human anatomical structure, body proportions, skeletal framework, muscle arrangement, and joint performance. Human flexibility has been integrated into the structure of humanoid robots.[246]

The human skeletal and muscular systems facilitate complex movements. By mimicking the microactuators composed of myosin and actin filaments, artificial muscles with anisotropic properties have been fabricated using patterned structures made from flexible thermoplastic polyurethane via 3D printing.[247] A kind of artificial neuromuscular fiber bundle, termed NeuroMuscle, was developed based on human skeletal muscles. These artificial fibers demonstrated muscle-like actuation and integrated sensing capabilities. The fibers were designed with a core-multishelled architecture comprising an LM core, an LCE actuation layer, and an adhesion sheath. This kind of artificial muscle showed potential to be applied in advanced systems to mimic the complex functions of human muscle.[248]

Ligaments, as essential soft tissues, also play a crucial role in human movement. A humanoid simulation model of the human shoulder complex, incorporating soft tissue ligaments and muscles, was developed. This model is capable of simulating both the skeletal structure and muscle arrangement, as well as the orientation of the ligaments. A detailed simulation model of the shoulder complex, including ligaments, was constructed, and it was verified that ligaments contribute to the stability of the articulating joint during movement.[249]

Human joints achieve low friction through the presence of synovial fluid and exudate within the joint capsule, working in conjunction with cartilage. By simulating the fluid exudation function of human cartilage, cartilage-like plates were fabricated using 3D-printed resin rubber with embedded PVA sponge. When subjected to a load, the plates deform and compress the liquid inside the sponge to provide lubrication. Upon load reduction, the plates recover their shape, absorbing the exuded fluid for reuse.[250] Based on the human sweat-evaporation mechanism, channels were created within the skeleton of the humanoid robot. Water is exuded from the surface of the skeleton to dissipate heat from the motors through the latent heat effect.[251]

The evolution of the human skeletal structure has also been explored to determine its optimality. The addition of an extra thumb can enhance the range of hand motion, as well as improving grip strength, precision, and dexterity. A 3D-printed sixth finger to the human hand as a hand-enhancement device increases the range of hand motion and improves grip strength, accuracy, and flexibility.[252]

Invertebrates

Mollusk-inspired soft robots

Mollusca is the second largest phylum in the animal kingdom with more than 130,000 species. Inspired by the way mollusks such as octopuses and squids propel themselves underwater with jets, researchers have developed modes of motion other than flapping fins. Renda et al. designed a soft-bodied underwater robot inspired by cephalopods. A hollow elastic shell was made of silicone, and four nylon cables were driven by a motor.

A check valve was installed at the water-suction hole, and the nozzle was composed of a flexible plate cylinder. Based on the Cosserat model, the mathematical model of the robot shell and the propulsion model were combined to realize underwater movement.[253] In addition, Wang et al. built a robot that could flap and swim, inspired by the powerful underwater propulsion mechanism of scallops. The robot used an artificial soft sail as a check valve to stimulate swimming; several support plates were fixed on the robot shell to adjust the shell-flapping process. The maximum average speed and instantaneous speed of the scallop robot were 3.4 and 4.65 body lengths/s, respectively. By adjusting the size of the injection aperture, the scallop robot could achieve high maneuverability.[254]

As a representative mollusk, octopuses exhibit a high degree of flexibility and diverse movement patterns. Mazzolai et al. studied the biology of octopus arms using ultrasound imaging to assess their morphology and tissue density. A robotic arm mimicked the junction fibers using braided tubes at a starting angle of 70°, with a conical silicone arm serving as the arm tissue. Eight radially arranged SMAs were used to mimic the movement of the transverse muscle, reducing the diameter of the arm while maintaining good elongation performance. Four longitudinal cables connected the arm from the base to the tip to mimic the action of the longitudinal muscles; they could contract within 1–2 s to achieve tension of 40 N.[176,177] Cianchetti et al. developed a bioinspired soft robot based on the movement of eight octopus arms in different states. For the different functions performed by the different arms, two arms were developed specifically for locomotion and for manipulation. The locomotion arm contained a crank mechanism that simulated the movements of an octopus as it crawled. The manipulation arm was driven by motor-driven cable and SMA actuators and was equipped with conductive textiles as a sensing system. The robot achieved a motion speed of 5 cm/s; the manipulator arm could achieve a force of 1.2 N by activating the SMA and a force of 10.8 N by operating the longitudinal cable.[255] Fras et al. proposed that an octopus robot could be entirely made of a soft material. It could be bent in different directions and angles by adjusting the pressure of the fluid in the different chambers. Three motion modes, namely forward propulsion, turning, and rotation around the spindle, were realized.[256]

The suction cups of an octopus produce a suction force in water through muscle contraction to achieve functions such as adsorption, crawling, and grasping objects. Consequently, several researchers have developed different suckers for operations such as grasping. Mazzolai et al. proposed a tendon-driven biomimetic octopus soft-robotic arm that could achieve suction of up to 3.6 N in air, 2.3 N in water, and 1.3 N in oil.[257] Jamali et al. developed a suction cup using a dielectric elastomer that mimicked the radial muscle of an octopus. The seven active-layer suckers produced a negative pressure of 1.5 kPa at a voltage of 6.5 kV.[151] Figure 4D shows an electronically integrated soft octopus arm that used stretchable liquid-metal electronic circuits to fabricate flexible sensors for sensing bending, suction, and temperature information. A wearable finger glove, which could be used for human-computer interaction, was designed to capture the gestures and bending movements of human fingers and provide feedback on the suction force generated on the bionic octopus arm.[222] Moreover, Wang et al. introduced a class of SpiRobs that were inspired by the logarithmic spiral that can be observed from octopus arms. These soft robots were fabricated through low-cost 3D printing with thermoplastic polyurethane (TPU) and simply used a tendon-driven actuation mechanism to achieve biomimetic curling and grasping motions. The modular design of logarithmic spiral geometry with discrete units showed outstanding scalability, enabling the creation of robots ranging in length from millimeter to meter scales to suit diverse applications.[258]

Cnidarian-inspired soft robots

Cnidarians rarely engage in active displacement movements. Their ability to move is limited and is driven by the contraction of myofibrils in epidermal muscle cells. For example, a hydra can perform telescopic movements. When stretched, its body length can reach 15–20 mm; when contracted, its body length is only 0.5 mm. This type of stretching is explosive and is caused primarily by the contraction of longitudinal myofibrils of the outer skin muscle cells. Similarly, the myofibrils of jellyfish form a thin layer of muscle rings on the lower surface and edge of the umbrella, causing it to contract regularly.[259] When the umbrella edge contracts, water inside the umbrella is ejected out, pushing the jellyfish along because of the reaction force.

Ren et al. developed a jellyfish-inspired untethered soft robot that could achieve moderate Reynolds-number operation using magnetic composite elastomer flaps driven by an external oscillating magnetic field to generate multiple controlled fluid-generated forces around its body. The robot's soft body could interact with these, exploiting the physical interaction to perform different predation-inspired object manipulation tasks. The proposed flap kinematics could inspire other jellyfish-like robots to achieve similar functionality (Figure 4E).[223] Li et al. were inspired by jellyfish to develop a soft robot made of hydrogel materials. A jelly-like muscle made of a DE-hydrogel-DE (DHD) structure with a water content of up to 83.3% and a muscle thickness of approximately 5 mm was proposed. The robot could achieve complex underwater motion with a maximum speed of 0.91 cm/s[260] Wang et al. developed a miniature jellyfish-inspired robot for underwater exploration. This robot addresses the limitations of existing designs by combining a bioinspired jet propulsion system with a novel flywheel steering mechanism, resulting in a small (diameter 110 mm), lightweight (318 g), and energy-efficient (10.5 W) robot. This design achieves an average speed of 5 cm/s and a maximum deflection angle of 25°, making it suitable for tasks like underwater exploration and environmental monitoring. While currently limited to vertical swimming in a water tank, future work will focus on enhancing depth capabilities, integrating autonomous navigation, and potentially incorporating soft intelligent materials for added functionality.[261] More recently, Wang et al. described a jellyfish-inspired robot using soft, electrohydraulic actuators for fast, efficient, and silent underwater propulsion. While challenges remain in material robustness, object manipulation capabilities, and miniaturization for complex real-world scenarios, this robot achieves speeds up to 6.1 cm/s while remaining remarkably quiet, enabling safer interaction with marine life. Importantly, the robot can also manipulate objects both with and without physical contact, mix fluids, adapt its shape, and steer, demonstrating a versatility that goes beyond simple locomotion. Multiple robots can cooperate on complex tasks, and a fully wireless prototype showcases the potential for autonomous environmental monitoring and remediation.[1]

Platyhelminthes-inspired soft robots

Planarians grow and shrink reversibly in response to environmental changes, allometrically adjusting and configuring existing tissues while maintaining appropriate proportions between organs as cell numbers change. Based on the repair capabilities exhibited by planarians, Mustard et al. proposed a toolkit for genetically encoded components that could facilitate bioengineering applications involving bioelectrical control to program the self-assembly of soft robots with complex structures.[262]

The head attachment organs of flukes and tapeworms (such as muscular suckers and small hooks) are fixed to the host tissue. Xie et al. proposed a long-term, noninvasive, and unrestricted method for delivering and implanting biosensors in the body via a swallowable implantable capsule robot (ICR). A small biosensor with a length and diameter of less than or equal to 30 and 11 mm, respectively, was attached to the intestinal mucosa for durations, working in a humid environment at body temperature. Based on *in vitro* testing, the adhesion was equivalent to that of a tissue attachment mechanism (TAM) manually deployed in an infinite vacuum during a previous study. During *in vivo* testing, the TAM was integrated with the ICR for approximately 52 h.[263]

Pseudocoelomata-inspired soft robots

Pseudocoelomic animals have a cavity between the body and intestinal walls, called a pseudocoelom, which is filled with coelomic fluid. As a hydrostatic skeleton, the coelomic fluid maintains the shape of the insect's body and assists in movement. Body-cavity fluids can also transport nutrients and metabolites and regulate and maintain the balance of water in the body.

Directly utilizing the activation energy and intelligence of living tissue in synthetic micromachines, Dong et al. used the genetics and nervous system of *Caenorhabditis elegans* to develop a biohybrid microrobot, creating an untethered, highly controllable, living soft microrobot. Using optogenetic and biochemical methods, the signaling between its neurons and muscle system was turned off, maintaining the optical excitation of muscle cells. Muscle-like light-driven actuators were deployed in the body to simulate the worm's primary crawling in a controllable manner. Through real-time visual feedback, closed-loop adjustment of the movement direction and destination of a single worm could be achieved.[264]

Annelid-inspired soft robots

Annelids can deform their bodies and adjust the friction at the contact point between their bodies and the ground to achieve propulsion. Morphologically, the body segments of annelids are separated by a septum, the body surface forming intersegmental grooves that serve as boundaries between the body segments. Such a physiognomy provides earthworms, a typical annelid animal, with the remarkable ability to navigate complex environments.[265] Earthworm-inspired soft robots categorize these robots into single-segment and multi-segment designs, using five main actuation methods: pneumatic, hydraulic, electric, magnetic, and hybrid driven. While pneumatic and electric actuation prevails in current research, emerging technologies like optical, sound, and thermal actuation recognize their potential to revolutionize the field.[266]

Inspired by earthworm locomotion, Das et al. present a soft-robot design using a unique peristaltic soft actuator (PSA) capable of generating bidirectional forces for versatile movement. The robot, composed of five modular PSA units, successfully demonstrates locomotion on planar surfaces, within granular media, and inside pipes, highlighting its potential for navigating challenging environments. By mimicking the earthworm's antagonistic muscle contractions and constant volume of fluid chambers, this design offers a promising approach for developing adaptable soft robots for subterranean exploration, pipe inspection, and other tasks requiring maneuverability in confined spaces. Further research is needed to optimize gait patterns, integrate sensory feedback, and test performance in complex natural environments.[267] In addition to this, a worm-like soft robot introduced by Liu et al. utilizes stacked Miura origami structures. By leveraging the inherent geometric properties of the origami design, the researchers amplify deformations from SMA actuators, generating continuous peristaltic waves for smoother, more efficient movement. The robot's segmented robotic skin, complete with anchoring bristles, is created through a streamlined dual-material 3D printing process.[268] Muff et al. engineered an earthworm-like robot built entirely from soft, modular polymer bilayer actuators to navigate tight spaces. Their design utilizes polyurethane with thermal expansion properties, eliminating the need for rigid components and achieving a higher blocking force than previous soft-bending actuators. While currently limited by speed and tethered operation, this design principle demonstrates its effectiveness in confined environments.[269] Wu et al. introduce a soft, energy-efficient crawling robot inspired by the locomotion of the mother-of-pearl moth caterpillar. The robot utilizes a thermal bimorph actuator composed of an LCE ribbon and a patterned silver nanowire (AgNW) heater embedded in a PDMS composite. The researchers achieved bidirectional locomotion by strategically patterning and heating the AgNWs, creating different temperature distributions and curvature changes along the robot's body. This controlled heating leads to varying friction at the front and rear ends of the robot, propelling it forward or backward based on which heating channel is activated. The robot successfully demonstrated both forward and reverse locomotion, achieving speeds of 0.5 and 0.72 mm/s, respectively, and it exhibited the ability to navigate a confined space with a height smaller than its own.[2]

In addition, Seok et al. proposed a soft robot that used antagonistic circular and longitudinal NiTi to drive a body woven with elastic fibers into a network tube to mimic earthworm movements. Two peristaltic motion modes, namely one segment contracting at a time and two segments contracting at a time, were modeled, tested, and compared. A numerical model of the network structure described the peristaltic motion and deformation. The robot was able to return to normal movement after several hammer blows.[270] Boxerbaum et al. studied the wriggling patterns of earthworms and developed a soft robot that used a braided tube structure to wriggle. A wave-motion model was developed and verified using the robot. It is surmised that the most important factor affecting the wave motion of the robot was the amount of slippage during transitions between the air and the ground.[271] Liu et al. designed a magnetic microswimming robot that imitated the morphology of annelids. Surface wrinkles could be controlled by applying a pre-strain on the substrate to achieve precise fabrication and consistent microswimming performance. The resulting annelid-like microswimmers exhibited efficient propulsion under an oscillating magnetic field, reaching peak velocities of approximately 100 μm/s. The speed and directionality of the microswimmers could be easily controlled by changing the field input parameters.[272] Ortiz et al. designed a digging soft robot inspired by polychaete-like creatures. The robot comprised three parts, one of which was a movable leading segment. This study investigated two leading-segment activation methods, namely periodic radial expansion and bidirectional bending. Research has shown that robots with a periodic radial expansion of their leading segments experienced the least resistance, whereas inactive robots experienced the greatest resistance. This study demonstrated that controlling the stiffness of the leading section was critical for achieving efficient underground movement.[273] Li et al. designed a bioinspired head inspired by bloodworms for the treatment of lymphedema.[274] A deformable soft mouthpart enabled contact sealing on unstructured surfaces. An adsorption success rate of 90% was achieved for phantom and human arms through contact perception and adaptive control. Bernth et al. present a robotic mesh worm for colonoscopy, featuring multi-DOF segments that enable forward/backward locomotion, anchoring, steering, and camera orientation through a unique bending-anchoring mechanism. This design simplifies control and allows the robot to adapt to varying colon diameters, potentially improving patient comfort and procedural efficiency. A prototype demonstrated promising results in a simulated colon, achieving higher speeds comparable to existing flexible endoscopes.[275]

Arthropod-inspired soft robots

Arthropods constitute the largest phylum in the animal kingdom. Their distribution is particularly wide, and their ability to adapt to the environment is impressive; they can survive in fresh water, deep sea, soil, air, and other environments. Inspired by the behavior of caterpillars that curled up to escape when they sensed danger, Lin et al. designed a flexible silicone-rubber robot driven by an SMA. Comprising a rotating hammer head, crimped body, and stable tail pair, the SMA drive wires were embedded in a cavity within the body. The anterior and posterior flexors combined to achieve a rolling speed of 300 rpm in 200 ms.[276] Moreover, the crawling mechanism of caterpillars inspired Sun et al. to develop a soft robot driven by cardiomyocytes composed of a claw-like snakeskin, parallel CNT-assisted myocardial tissue layer, and structural color indicator layer (Figure 4F). The claws assisted the entire soft robot in completing directional movement during myocardial cell contraction. The robot could run along a track and exhibit different running speeds based on the number of myocardial cells.[224] Another special arthropod, the water strider, could rotate the curved tips of its legs inward at a relatively low descent speed, with a force slightly less than that required to break the surface of the water. Song et al. developed a water-strider-inspired robot using hydrophobic-coated steel-wire legs and a piezoelectric single-crystal T-shaped actuator, enabling it to move on the water surface at a speed of 3 cm/s.[277] Having achieved this feature in a surface-tension-dominated hopping robot, Koh et al. explained the fluid dynamics involved and applied them to develop a pulsing mechanism inspired by water striders to maximize their movement on water. A 68-mg mass-hopping robot was built, and its ability to jump on water with maximum momentum transfer was verified.[278]

Insects have also provided researchers with considerable inspiration. Most insects use a tripod gait while running, maintaining at least three legs on the ground at any given time. This gait allows insects to quickly navigate 3D terrain. Ramdya et al. optimized the walking speed of this model under different simulation conditions and proposed a dynamically stable six-legged "bipedal" gait that was not evident in nature.[279] Inspired by the high-frequency rapid cyclic motion of arthropods, Wu et al. developed a soft robot with a curved, fast-scale, ultrahard piezoelectric structure. Under 850-Hz alternating current conditions, the robot achieved a relative speed of 20 body lengths/s, remaining strong and mobile even under a load of 59.5 kg.[280] Cockroaches can move through narrow gaps by compressing up to 40% of their body thickness and can move up to 20 times their body length/s in confined spaces. Based on these findings, a soft robot of length 15 cm and weight approximately 150 g was designed. It possessed high flexibility and rapid mobility and was capable of crawling effectively in complex environments. The robot could move at a speed of 1.5 m/s in narrow spaces and traverse gaps that were 50% smaller than the robot's thickness.[281] Moreover, Saranli et al. developed a six-legged robot inspired by cockroaches, where each leg is independently driven by a dedicated motor. This design enables the robot to traverse uneven and fragmented terrains effectively.[282]

Faber et al., inspired by the earwig's wing folding ability, developed a spring origami model. A replica of the wing pattern was fabricated using polymer 4D printing. Unusual self-locking, fast-deformation, and geometrically tolerant folding modes were achieved.[283] Chen et al. developed a biomimetic robot that could move in air and water. In both liquid and gas media, the robot drove its flapping-wing motion using piezoelectric actuators. During the transition from liquid to gas, the electrolytic plate produced hydrogen electrochemically in water, with the thrust generated by the igniting hydrogen enabling the robot to complete the transition between the two media. However, this version of the robot lacked perception, making it impossible to achieve rapid attitude and positional feedback.[284] Improvements were made in subsequent work, and a process was designed for developing a microrobot that could fly using soft artificial muscles. The robot was driven using multilayer DEAs, each weighing 100 mg, with a resonant frequency of 500 Hz and a power density of 600 W/kg. The robot could sense and withstand collisions with surrounding obstacles. It featured open-loop control, passive stable-ascent flight, closed-loop control, and hovering flight capabilities.[285] Karásek et al. demonstrated a tailless, autonomously programmed flying-insect robot that mimicked the fast-turning flight movements of fruit flies. Four 14-cm wings were driven by motors to produce a flapping frequency of 17 Hz. They could actively control the rolling, pitch, yaw, and thrust with four DOF. The yaw, roll, and pitch torque were programmed to coordinate with each other to achieve yaw rotation. The robot demonstrated that yaw rotation was not directly generated but was caused by the coupling of other torques and aerodynamic forces caused by motion.[286] Jafferis et al. built a 90-mg bionic insect robot that used piezoelectric materials to drive four wings. Compared with similar two-winged designs, the aerodynamic efficiency of the flapping-wing mechanism improved by 29%, achieving a thrust-to-weight ratio of 4.1 to 1. Onboard electronics, such as photovoltaic arrays and signal generators, could also realize chargeable and untethered flights.[287]

Echinoderm-inspired soft robots

The unique biological characteristics of echinoderms are fascinating for researchers to take inspiration for developing soft robots. Typical species of echinoderm include starfish, sea urchins, and sea cucumbers. Modeling and controlling underwater soft robots can be challenging because of their high DOFs and complex coupling with water. Inspired by the rapid and reversible changes in dermal stiffness observed in sea cucumbers, Capadona et al. reported a polymer nanocomposite material that mimics this behavior by regulating interactions between collagen fibers. The material consists of a rubber-like matrix polymer and rigid cellulose NFs. When exposed to chemical regulators that mediate NF interactions, the tensile modulus reversibly decreases by up to 40-fold.[288] Du et al. proposed a method that used the latest developments in differentiable simulations and differentiable analytical fluid dynamics models to assist in modeling the control of underwater soft robots. They applied this approach to starfish, a custom soft-robotic design that was easy to fabricate and operate. Their approach began with data obtained from real robots and alternated between simulations and experiments. Experiments showed that the correct use of the gradient of a differentiable simulator not only reduced the gap between simulations and reality but also improved the performance of open-loop controllers in actual experiments.[289] Inspired by the starfish, Yang et al. developed a soft robot with omnidirectional adaptive motion capabilities. The robot was designed to imitate the microtube structure of a starfish, which enhanced its driving performance, reduced movement resistance from the ground, and improved its ability to overcome obstacles. Because of the radially symmetrical shape of the starfish, the robot could achieve omnidirectional movement when driven by a magnetic field. The robot performed successful locomotion demonstrations, including moving in an "S" trajectory, adapting to wet and gravel surfaces, and overcoming obstacles, demonstrating the robot's potential application in harsh environments.[290]

Summary and outlook

This section provides a comprehensive overview of the advancements in animal-inspired soft robotics, highlighting how researchers draw inspiration from both vertebrates and invertebrates to develop robots with enhanced locomotion, adaptability, and environmental interaction. The section underscores the significance of biomimicry in addressing complex robotic challenges by emulating the structural and functional principles observed in nature.

One of the foremost challenges in this field is using the principles of the complex locomotion mechanisms of animals within the constraints of synthetic materials and actuation technologies. For instance, fish-inspired robots have made strides in underwater propulsion by mimicking the undulatory movements of fish, utilizing materials like DEs and biohybrid constructs with cardiomyocytes. While these designs achieve high maneuverability and speed, they often depend on external stimuli or tethered power sources, which limit their operational autonomy and practical deployment in real-world aquatic environments. To overcome these limitations, there is a pressing need to integrate onboard power systems and develop advanced control algorithms that can manage the dynamic and unpredictable nature of underwater settings.

Similarly, amphibian-inspired robots attempt to navigate terrestrial and aquatic environments by emulating the dual locomotion capabilities of amphibians. Developing hybrid propulsion mechanisms that function efficiently in both media presents significant engineering challenges. Trade-offs often arise between the added weight and complexity of systems optimized for aquatic propulsion and the agility required for terrestrial movement. Advancements in lightweight, adaptive materials and versatile actuation systems are essential to enhance the robots' adaptability and efficiency across diverse environments.

Material innovation is emerging as a critical factor influencing the progress of animal-inspired soft robotics. While soft materials such as silicones, hydrogels, and elastomers provide the necessary compliance for safe interaction with humans and adaptability to unstructured environments, they frequently lack the durability and strength required for sustained operation, especially in harsh or variable conditions. The development of smart materials that combine flexibility with robustness and possess the ability to alter their properties in response to environmental stimuli is vital. Such materials could significantly enhance the functionality and reliability of soft robots, enabling them to withstand mechanical stresses and environmental degradation over extended periods.

Managing the high degrees of freedom and nonlinear dynamics inherent in soft robots remains a substantial challenge. The compliance and deformability that grant these robots adaptability also introduce unpredictability in their movement and response to external forces. Implementing advanced control strategies, including machine-learning algorithms and adaptive control methods, could improve the precision and responsiveness of soft robots. These approaches would allow for real-time adjustments to the robots' behavior based on sensory feedback, enhancing their ability to perform complex tasks in dynamic environments.

Energy efficiency and autonomy are also pivotal concerns. Many animal-inspired soft robots rely on external power sources or tethers, restricting their operational range and limiting their applicability in scenarios that require extended or untethered operation, such as environmental monitoring or search-and-rescue missions. Research into lightweight, high-capacity energy-storage solutions and energy-harvesting methods is essential to facilitate untethered operation. Innovations in this area could enable the development of fully autonomous soft robots capable of long-duration missions without the need for frequent recharging or direct power supply.

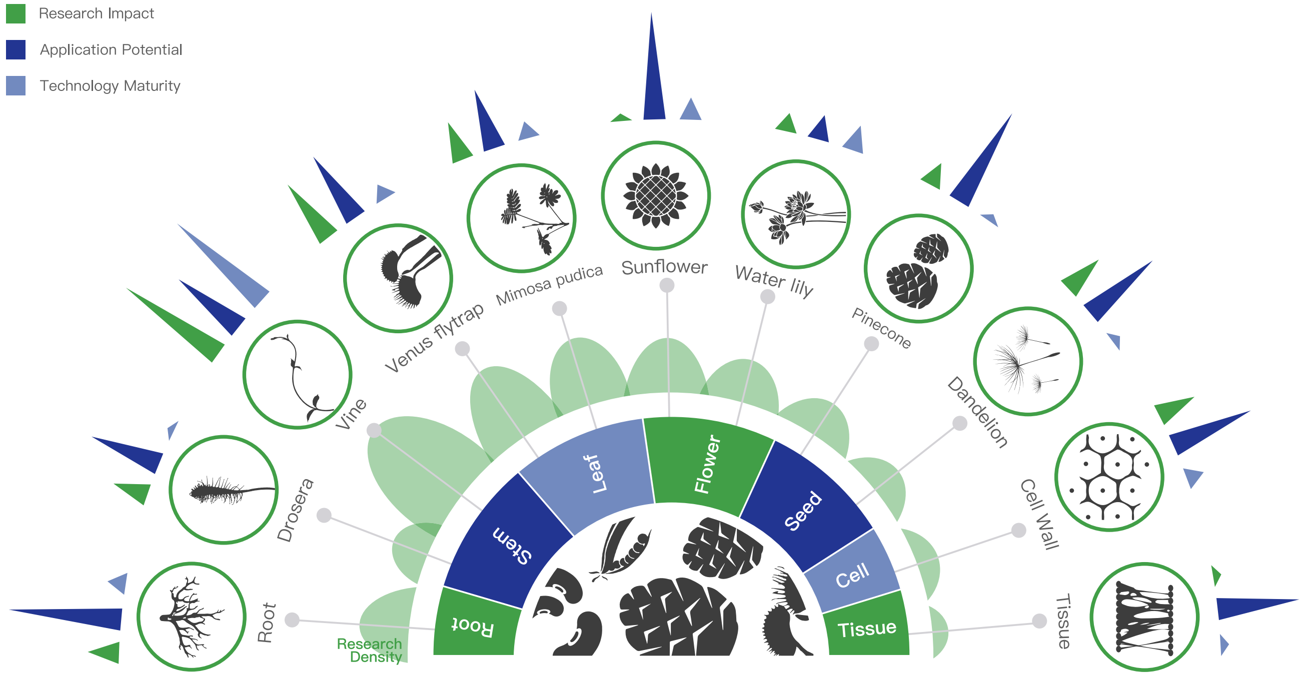

Figure 5. The distribution of different plant models used in soft-robotics research in recent years
Plants are fascinating models for engineering soft robots due to their remarkable capability of movements without complex systems like the central nervous system and muscles. Here, the area under each plant model in the middle ring indicates the research density of a given plant model in current soft-robotics research, whereas the graph bars of the outer ring indicate the research impact, application potential, and technology maturity involved in using a particular plant model for the design of soft robots.

Mollusk- and annelid-inspired robots demonstrate remarkable potential due to their flexible structures and ability to navigate complex environments. Mollusk-inspired robots, particularly those emulating octopuses, offer high DOFs and manipulability suitable for tasks in unstructured settings. They face challenges controlling intricate systems and integrating sensory feedback for nuanced environmental interactions. Annelid-inspired robots, modeled after earthworms, successfully mimic peristaltic motion for navigation through confined spaces and complex terrains. Despite their effective locomotion strategies, optimizing movement efficiency and developing untethered power supplies remain ongoing challenges.

PLANT-INSPIRED SOFT ROBOTS

Plants are fascinating models for engineering soft robots due to their remarkable capability of movements without complex systems like the central nervous system and muscles. They dig deep into the ground and extend their roots.[291] To avoid threats and protect themselves from thermal damages, predator, and other potential harms, plants curl and fold their organs.[292] Their leaves regulate the internal vapor pressure by opening and closing their stomata,[293,294] and carnivorous plants capture prey with rapid movements.[295–297] For reproduction, plants open their seed pods[298,299] and disperse their seeds,[300–302] and some seeds even burrow into the ground.[303,304] A schematic of distribution of different plant models used in soft-robotics research in recent years is presented in Figure 5.

Inspiration from leaves

Leaves are vital organs for all higher plants, facilitating the photosynthesis process that generates nutrients essential for growth. In the natural world, leaves exhibit a wide variety of shapes and features to adapt to diverse environments. Some of these forms are particularly noteworthy and have become a focal point for analysis. Consequently, plant leaves have increasingly captured the interest of researchers in the field of soft robotics, who look to these natural structures for inspiration in developing innovative, adaptable robotic systems.

Venus flytrap

The Venus flytrap has been recognized as a potential bio-model due to its ability to execute rapid snap transitions in response to external stimuli. Researchers have replicated this unique biological feature, creating a responsive surface with an array of convex microlenses capable of performing the same “snap-to-convex” process in even less time.[305] Additionally, an artificial muscle was developed using a bilayer structure composed of poly(methyl methacrylate) and GO, designed to mimic the motion of a Venus flytrap under light stimulus. This system incorporates gold nanorods (AuNRs) to efficiently transform light into heat. Upon photothermal heating, bending occurs due to the mismatch in deformations between the two layers.[306] Another approach is demonstrated in Figure 6A, which involved a light-responsive liquid-crystal elastomer paired with an optical fiber, forming a special soft robot that can promptly capture an object entering its detection zone.[307] Inspired by the snap-through buckling used by the Venus flytrap to catch prey, Yasuda et al.

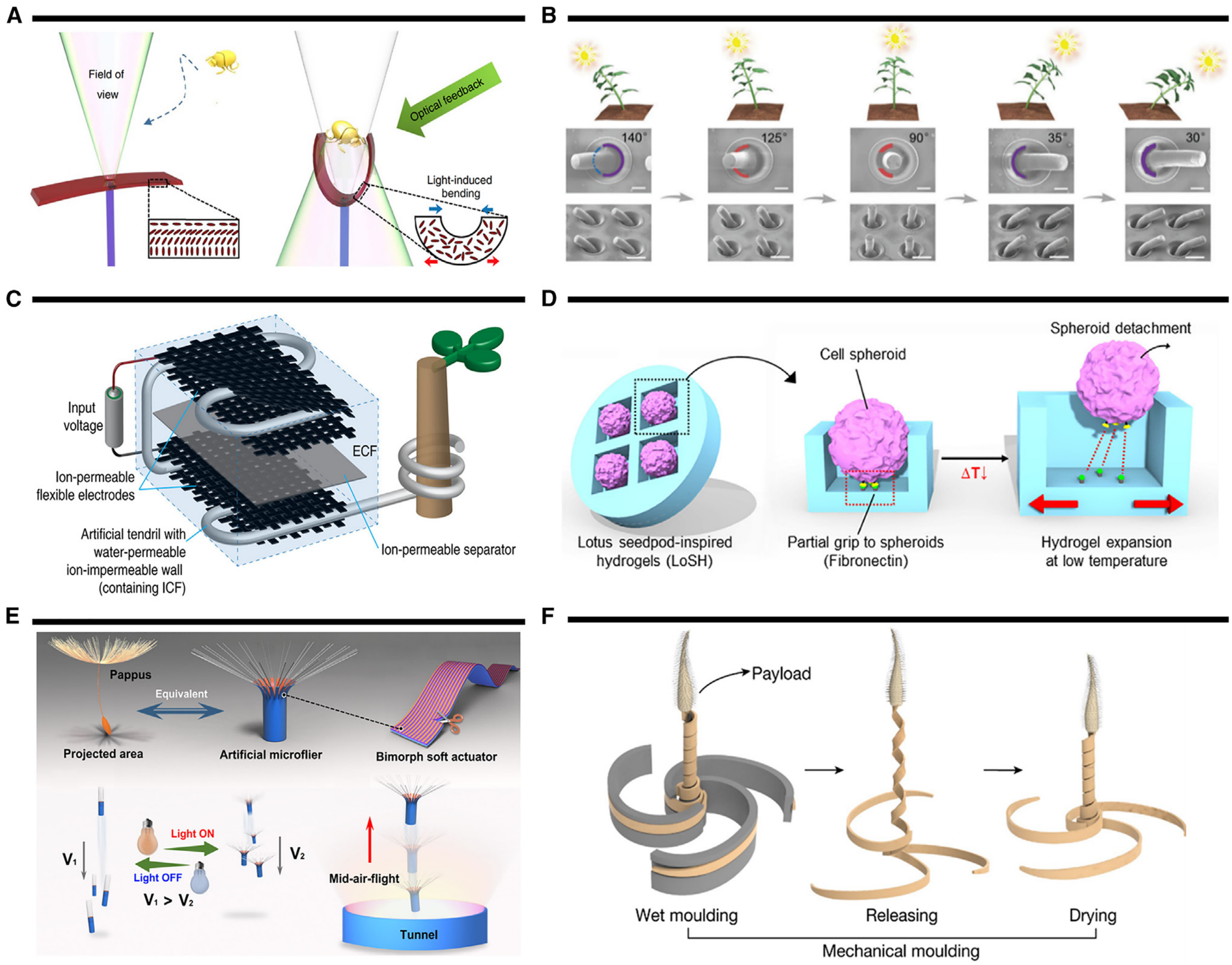

Figure 6. Soft robots developed with inspiration by plant models

(A) A flytrap-inspired light-triggered soft robot. Reprinted with permission from Wani et al.[307] Copyright 2023, Springer Nature.

(B) SEM images show the evolution of soft micropillars from left to right *in situ* tuning mimicking the behavior of a sunflower. Reprinted with permission from Zhang et al.[311] Copyright 2018, Wiley-VCH.

(C) Tendril-inspired soft robot based on osmotic actuator. Reprinted with permission from Zhang et al.[312] Copyright 2019, Springer Nature.

(D) Lotus seedpod-inspired hydrogels with a spheroid culture and attachment mechanism. Reprinted with permission from Kim et al.[313] Copyright 2019, Elsevier.

(E) Light-controllable artificial fliers inspired by dandelion morphology. Reprinted with permission from Chen et al.[314] Copyright 2023, Springer Nature.

(F) Artificial seed awns made of wood veneer with natural hygromorphic properties, effectively burying seeds into the soil. Reprinted with permission from Luo et al.[315] Copyright 2023, Springer Nature.

developed a leaf-like origami gripper by selectively controlling the creases.[308] Given the power-amplified movements provided by snap-through buckling, this mechanism also enabled highly effective jumpers. Kim et al. developed a polymer gel jumper that leverages internal stresses to drive snap-through buckling, induced by differential solvent evaporation on curved surfaces.[309] Focusing on the force-displacement response of snap-through buckling, Zhang et al. developed a micro-actuator for gripping and releasing microscopic objects.[310] This two-way actuator features a curved beam unit confined by a rigid frame and a laminated spring composed of two identical curved beams in series.

Mimosa

The *Mimosa* plant has also been a popular template for biomimetic research in soft robotics. Its reversible open-close response has been emulated using bilayer structures. One significant development is a *Mimosa*-inspired bilayer hydrogel actuator that generates movements in response to temperature changes. This actuator uses two hydrogel layers with different critical solution temperatures to achieve controlled action.[316] Following this, a bilayer arrangement of PNIPAM-PEGDA was used to create an artificial *Mimosa*, allowing regulated opening and closing by varying temperature or solvent concentration.[317] Beyond bilayer structures, a novel actuator design incorporating hydrogen bonding has been employed to respond to multiple stimuli, including changes in humidity, temperature, and light intensity.[318]

Drosera

The predatory behavior of *Drosera* (sundew) leaves has also garnered significant attention. Inspired by this, an artificial model using an asymmetrical structure and materials such as moisture-responsive GO and MXene was developed to replicate the rapid capture process.[319] Further advancements led to the creation of a self-sensing biomimetic *Drosera* capable of executing a closed-loop controlled response to external stimuli. This sophisticated design includes an actuating layer, a flexible heater, a strain sensor, and a piezoelectric sensor, ensuring the response is programmable, reversible, and highly sensitive.[320]

Other leaves

Deeply mimicking a natural leaf requires replicating both its intricate architecture and photosynthetic mechanisms, as showcased by MXene-cellulose composite (MXCC) bilayer soft actuators. In this design, MXene nanosheets function like palisade mesophyll cells that harvest light energy, cellulose NFs serve as the vein skeleton providing robustness, and polycarbonate membranes emulate stomata to facilitate water transport. This multifaceted biomimicry makes this leaf-inspired actuator a revolutionary technology in the development of smart soft robots and devices.[321]

Inspiration from flowers

Flowers are essential organs for plant propagation. In the natural world, they have evolved intelligently to adapt to changing environments. A wide variety of flowers exist, a few possessing unique features that have prompted extensive research efforts to understand and learn from them.

Lily

The lily flower exhibits adaptive behavior, blossoming in moist conditions and curling up in drier environments to prevent dehydration. Inspired by this mechanism, a soft robot sensitive to humidity and temperature has been developed. This robot incorporates an organic polymer-crystal hybrid material that facilitates strain-induced bending in response to stimuli. Sensitivity assessments indicate that the artificial lily responds within milliseconds, and its durability has been confirmed through 1,000 repeated test cycles.[4]

Sunflower

The distinctive architecture and heliotropism of the sunflower have captivated researchers aiming to design soft robots. To emulate the sunflower's motion, which results from differential lateral stem growth, a polystyrene film with shrinkage properties was investigated. A key difference lies in the stimulus: while natural sunflowers adjust their morphology in response to light variations, the artificial counterpart responds to temperature changes (Figure 6B).[311]

Other flowers

The configurations of some flowers have significantly inspired the design of soft grippers across various fields. The bilayer structure, which consists of different materials generating uneven expansion rates under stimulus, has been extensively analyzed in numerous studies. GO and RGO are popular materials used in these structures. A GO/RGO-based artificial flower with a bilayer structure was designed to demonstrate motion capture in response to changes in humidity.[91] Integrated with swellable metal-organic frameworks (MOFs), a shape-transform-reversible soft gripper was developed, showing potential in micromanipulation, automation, and robotics. Both light and humidity were employed as external driving sources for programmable control of the gripper's actuation.[322] Similarly, a larger-scale soft gripper combining carbon fiber and a soft pneumatic actuator demonstrated a fast response and a wide fitting range in gripping objects of various shapes, sizes, and weights.[323]

Inspiration from stems

Plant stems, known for their ability to grow, adapt, and morph in response to environmental conditions, serve as a unique model for developing soft robots. Researchers have extensively attempted to create adaptive, efficient, and resilient soft robots inspired by the properties of plant stems.[324,325]

Galium aparine

Galium aparine, a typical climbing plant, grows with natural micropatterned hooks. These flexible hooks, which strongly attach to hosts, have garnered significant interest. In one study, the 3D direct laser lithography technique was employed to construct artificial hooks that morphologically emulate the ratchet-like attachment mechanism of *G. aparine*. The performance of these hooks was verified through a series of tests, including measurements of pull-off and shear forces on rough surfaces. The microprinted hooks demonstrated high potential for use in building interlockers for soft robots and microrobots, as well as applications in the textile industry and biomedical fields.[326]

Tendril

Tendril, originating as a seedling of the stem branch in climbing plants, extends the plant's territory by capturing and wrapping around nearby objects to support further growth. A tendril-like soft robot, built with a reversible osmotic actuator and crafted from biocompatible materials, is illustrated in Figure 6C. This delicate robot operates on electrical stimulation, requiring only 1.3 V. To assess its designed reversibility, the robot underwent multiple motion cycles, highlighting its potential for versatile applications.[312] In a related study, a multi-stimuli-responsive actuator was designed to morphologically mimic the natural tendril, functioning as a helical gripper. A graphene GO/PPy bilayer was introduced as an innovative component.[327] A more recent study utilized four-dimensional (4D) printing to layer humidity- and temperature-sensitive materials, creating an uneven distribution of active tissues that enable self-morphing.[328]

Inspiration from seeds

In the plant kingdom, seeds play a crucial role in the propagation of plants. Throughout the extensive evolutionary history of plants, various ingenious mechanisms have been developed to disperse seeds efficiently. The plant seeds that are dispersed using wind have evolved various morphological adaptations to travel a large distance. These adaptations include parachute-like structures with intricately branched hairs, such as Eurasian dandelion (*Taraxacum officinale*)[25]; helicopter-like seeds with a wing able to autorotate as they fall, such as samaras of maple trees[27]; and glider-like shapes with lateral wings, as seen in the seeds of the tropical vine *Alsomitra macrocarpa*.[28] Drawing inspiration from these intelligent adaptations in plant seeds, scientists have invested significant effort into developing soft robots that possess similar abilities to those of plant seeds.

Pine cones

Pine cones demonstrate a natural protection mechanism against humidity or rain; they open when the atmosphere is dry and close when the air becomes moist or during rainfall.[329] An artificial pine cone, featuring a cellulose microfibril reinforcement architecture, was introduced to emulate the shape-changing behavior of the natural pine cone.[330] Differing from moisture as a stimulus, a solvent-induced soft actuator made of poly-ether-ether-ketone (PEEK) and created with 3D-printing technology, exhibited precise programmable deformation and substantial load-carrying capacity.[331]

Orchid tree seedpods

The seedpods of orchid trees exhibit a fascinating natural response to varying environmental conditions. When completely dehydrated, they burst apart into two twisted layers. To mimic this mechanism, bilayer-structured synthetic seedpods were designed to replicate the behavior of the real ones.[330]

Wheat awn

Wheat plants use the awns on their seeds as a dispersal mechanism. These awns are sensitive to humidity; they maintain a helical structure under typical dry conditions and rapidly elongate to propel the seed when exposed to moisture. Inspired by this natural phenomenon, a hygrobot was developed. This device comprises both inactive and humidity-sensitive active layers, designed to emulate the behavior of the wheat awn.[35]

Lotus seedpods

The lotus seedpod serves as another compelling bioinspired model. It remains attached to the mother base via a special funiculus and is released by breaking this connection. Inspired by this mechanism, a hydrogel microwell plate was developed; each well contains a cell spheroid bound by fibronectin (Figure 6D). As the temperature increases, the hydrogel plate expands, generating shear force at the connecting surface between the fibronectin and the spheroid, which induces bond breaking and spheroid detachment.[313]

Dandelion

Inspired by dandelion morphology, researchers have developed passive artificial fliers that generate separated vortex rings and stay afloat for a long time in the air.[332,333] Recently, artificial dandelions made from smart materials have been created with features such as light-controllable takeoff and landing[334] and adjustable falling velocity in response to external stimuli (Figure 6E).[314] Chen et al. developed a tubular dual-flap microrobot as an actuator, which controls its descent speed by adjusting the opening angle under light exposure. The robot achieved a flight duration of 8.9 s and a maximum flight height of 350 mm.[314] Yang et al. developed miniaturized artificial rotary gliding fliers inspired by maple samaras.[335] These fliers use an azobenzene-crosslinked liquid-crystal network (azo-LCN) for photochemical actuation, enabling reversible and bistable shape morphing under UV and visible light. By adjusting the UV dose, the terminal velocity and spinning rate of the artificial seeds can be controlled.

Inspiration from roots

The root serves as the primary nutrition supplier to the plant, exhibiting an innate ability to navigate through complex soil structures. It can sense minute changes in soil conditions and adaptively modify itself to foster better growth patterns. The mechanisms of plant roots in achieving this capability provide invaluable cues for researchers aiming to build effective soft robots.

In one study, a root-like soft robot was designed, featuring a tubular body, a growth-oriented head, and a sensor-embedded tip. This robot demonstrated the ability to move within a medium and exhibited growth capabilities under high pressure.[336] Building on this, an improved model was subsequently developed. This latest model displayed abilities for obstacle avoidance, penetration, and passive morphological adaptation.[337] In a related study, the root of the *Zea mays* plant was chosen as the biological template, and 3D printing technology was employed to fabricate the artificial root. Its capabilities in terms of penetration and movement were thoroughly analyzed and deliberated.[338] Furthermore, a root-inspired soft robot has been specifically designed for burrowing. A recent iteration of this robot demonstrated the ability to adeptly manage subterranean lift and drag forces while also featuring a steerable body below ground.[339]

Inspiration from plant tissues

The behavior of tissue, an aggregation of cells to perform a specific function, is significantly influenced by the arrangement of these cells. Compositional inhomogeneity within tissue leads to strain mismatches and, consequently, complex deformations in various plant organs. Plants create this inhomogeneity by arranging cells in multiple layers or specific patterns, a strategy that has been mimicked by artificial systems.

Multilayers

In plants, hygroscopically driven tissues often consist of two layers: an active layer that deforms in response to change in environmental humidity and an inactive layer that is insensitive to moisture content. The active layer contains secondary cell walls characterized by cellulose microfibrils wound helically around the cell. The tilt angle of these fibrils with respect to the cell axis determines the hygroscopic expansion ratio and direction.[340] When these fibrils wind the active cell walls in a way to expand or shrink uniaxially, the bilayer bends or unbends with humidity variation. Such bending actuation can be found in pine cones[298] and wild wheat.[303] Additionally, when the winding of fibrils is tilted so as to induce helical coiling of the individual active cells, the entire bilayer also helically coils or uncoils, as seen in the seed awns of *Erodium* and *Pelargonium* species.[303]

Inspired by the design strategies of those seeds, Jeong et al.[341] developed a shape-morphing film actuator using PDMS, which has a high coefficient of thermal expansion. They incorporated SU-8 microstructures to mimic cellulose microfibrils, guiding the direction and extent of expansion. This actuator can bend, coil, twist, and transform into complex shape. Similarly, Lin et al.[342] and Zhang et al.[343] reported stimuli-responsive polymers integrating aligned CNTs or an aligned glass-fiber network to mimic plant cellulose microfibrils. These actuators exhibit programmable bending and coiling behaviors in response to acetone vapor or humidity. Luo et al.[315] employed wood veneer, which exhibits hygromorphic properties along with its anisotropic internal fiber orientation. Figure 7F demonstrates artificial seed awns based on such material that can effectively bury the seeds into the soil. Artificial actuators only consisting of unidirectionally aligned hygroscopic polymer fibers on an inactive layer were able to exhibit various deformation modes from twisting, helical coiling to bending depending on the relative fiber orientation to the longitudinal axis of the fibrous sheet.[35,344]

Patterned structures

Plant morphogenesis, the formation of functional organs, is driven by differential growth in plant tissues. Local growth rates within a meristem result in nonuniform expansion and growth strain mismatches, altering the shape of plant organ, influenced by genetic and environmental factors.[345,346] Dictated by genes, the differential growth patterns in plant leaves and flower petals create a wide variety of complex 3D shapes, such as saddle shapes and rippled edges.[347,348] Growth rates vary in response to environmental stimuli including gravity, light, temperature, and touch.

The differential-growth-induced mechanical deformation strategy of plants has been applied to soft actuators by patterning expandable regions. Hu et al.[318] used starch-based natural polymers, inducing partial gelatinization by exposing specific areas to NIR light. This selective gelatinization alters the polymer network, creating regions with different swelling ratios due to variations in hydrogen bonding and water uptake, resulting in a bending motion. Similarly, Cakmak et al.[349] controlled the swelling regions by using patterned curing of a UV-curable adhesive embedded with hygroscopic *Bacillus subtilis* spores. Photolithography was employed to precisely pattern the adhesive, creating active and inactive layers that enable the formation of complex 3D structures responsive to humidity changes. Chen et al.[350] used a related approach by programming spatially differential swelling ratios through sandwiching the active layer between inactive layers and manipulating the distribution of the inactive layer. This method enabled the creation of bending with various curvatures, coiling, and complex 3D shape changes.

Inspiration from plant cells

Plant cells consist of a gel-like cytoplasm with various organelles, surrounded by a semi-permeable plasma membrane and a rigid cell wall. This cell wall is a composite structure made of a soft matrix primarily composed of pectins and hemicelluloses, embedded with rigid cellulose microfibrils that provide mechanical strengths, such as tensile strength.[299] The shape of plant cells varies widely with their maturity and location within the plant. Plants achieve targeted movement by precisely regulating cell morphology, cell wall structure, and elasticity, which provide rich sources of inspiration for soft robots.

Cell morphology

The combination of a swellable core and a rigid shell enables plant cells to generate significant pressure through osmotic water absorption. This osmotic pressure, referred to as turgor pressure, is the internal hydrostatic pressure exerted by the cell's cytoplasm against the cell wall. Typical turgor pressures in plant tissues range from 0.1 to 6 MPa, demonstrating the potential for powerful osmotic actuation in soft actuators.[351,352] Na et al.[353] designed a hydrogel actuator inspired by this natural core-shell structure of plant cells that can exert a large stress of 0.73 MPa using $\sim$1 cm^3 of hydrogel. By wrapping a hydrogel with a stiff membrane, they emulated the plant cell structure to overcome the limitation of low actuation forces inherent in hydrogels.

Different cell shapes lead to varied mechanical properties and responses to turgor pressure. Elliptical and elongated polygonal-shaped cells deform more along the shorter axis due to the stress concentration at the vertices and edges, causing anisotropic deformation.[354] For example, the seed capsule of the desert ice plant (*Delosperma nakurense*) opens mechanically when hydrated due to large, directed deformation in its valve driven by anisotropic honeycomb-structured elliptical cells.[298] One prominent application of the cell shape-mediated actuation is in adaptive aircraft wings. These wings optimize aerodynamic performance during different flight phases, utilizing pressure-actuated cellular structures with honeycomb.[355] They can transition from a high-lift configuration for takeoff to a low-drag shape for cruising, maximizing aerodynamic efficiency. Recently, pressure-actuated cellular structures have been integrated into soft actuators, enabling rapid, controllable, and complex 3D shape transformations.[356]

Cell wall patterns

Plant cell walls are fibrous structures composed of layers of stiff cellulose fibers crosslinked by a soft matrix. The cellulose microfibrils strongly resist deformation along their axis but less so in other directions. When these fibers align uniformly, they impart anisotropic properties to the cell wall, regulating its stiffness. The tilt angle of the fibrils with respect to the cell axis, known as the microfibril angle, determines the stiffness of the cell.[304] Consequently, the fiber alignment controls the direction of cell deformation to achieve targeted movement. In guard cells of stomata, the fibrils are oriented perpendicular to the longitudinal central axis of the cells. This alignment contributes to longitudinal expansion, leading to bending movements in response to increased turgor pressure.[293]

Inspired by the anisotropic expansion of plant cells, Sydney et al.[357] embedded and aligned stiff cellulose fibrils within hydrogels through 3D printing. This created architectures with spatially and temporally patterned swelling anisotropy, enabling the hydrogels to undergo complex shape changes upon absorbing water. Similar soft actuators using a polymer matrix embedded with liquid-crystal molecules that respond to thermal stimuli have been reported.[358,359] These actuators exhibit multidirectional bending, and, by combining multiple units, multifunctional soft grippers and untethered soft robots were developed. Kim et al.[360] incorporated electrolyte nanosheets into hydrogel actuators and utilized the temperature-modulated electrostatic interactions between the nanosheets to induce significant elongation and contraction of the hydrogel.

Cell wall elasticity

The elasticity of the cell wall is influenced by cellulose microfibrils, composed of high-molecular-weight glucan chains arranged in partially crystalline bundles and held together by hydrogen bonds. Enzymes such as pectin methylesterases (PMEs) modify pectin to loosen the cell wall, and this enzymatic activity facilitates cell wall expansion. Filamentous cells, such as protonemata, root hairs, and pollen tubes, exhibit highly directional growth. Their polar growth is regulated by controlling cell wall elasticity at specific sites with the secretion of materials that flex the cell wall, coupled with turgor pressure-driven expansion.[291]

Mimicking the polar growth of plant cells, Park et al.[361] developed a tip-growing polymer system using nonsolvent-induced phase separation of a cellulose acetate (CA)-acetone solution. In this process, acetone diffuses into water, causing the CA to precipitate and form a stiffening gel at the interface. This keeps the tip weaker due to the continuous supply of fresh CA-acetone solution, allowing the system to grow a cylindrical body. Other growing robots have been developed by controlling the expansion rate at the tip by supplying new materials through either unfolding thin tube walls[362] or using material extrusion processes like fused deposition modeling (FDM).[363]

Summary and outlook

This section has explored how various plant structures—including leaves, flowers, stems, seeds, roots, tissues, and cells—have inspired the development of soft robots. By emulating mechanisms such as the rapid snapping of the Venus flytrap, humidity-responsive movements of pine cones and wheat awns, the coiling tendrils of climbing plants, and the soil-digging strategies of roots, researchers have created robots capable of adapting their morphology, responding to environmental stimuli, and performing complex tasks. In addition, design strategies of plant tissue structures, such as multilayer compositions and patterned cell walls, have led to the creation of soft actuators capable of programmable shape transformations.

Despite these advances, the potential of plant-inspired systems remains vast and largely untapped. Many plants exhibit fascinating movements that have yet to be fully explored in robotics. Traditional plant movements often rely on osmotic pressurization or hygroscopic swelling, mechanisms limited by the diffusivity of fluids through cell membranes and walls, resulting in slower response times. To overcome these constraints, certain plants cleverly utilize stored mechanical energy to achieve rapid, amplified movements. Interestingly, similar rapid movements are also observed in fungi, which, like plants, are sessile organisms. Fungi thus represent an exciting and largely unexplored source of bioinspiration for the development of future robotic systems. For example, explosive seed dispersal in plants like *Impatiens glandulifera* relies on stored elastic energy in pre-stressed structures, which fracture when triggered by touch.[302] Similarly, the carnivorous plant *Utricularia australis* captures prey using suction traps that employ both snap-through mechanisms and pre-stored mechanical energy.[297] A fungus, Ascomycota phylum, launches spores (ascospores) using tubular sacs called asci, which act like miniature water cannons.[364] Turgor pressure builds up within the ascus as water accumulates, stretching its walls until the spores are explosively released at a critical threshold. Utilizing these high-speed, energy-efficient mechanisms could address key limitations in current soft robotics—namely, slow reaction times and low mechanical strength—paving the way for more advanced, plant-inspired soft robots.

MICROORGANISM-INSPIRED SOFT ROBOTS

Microorganisms are an essential source of inspiration for the development of soft robots because of their outstanding adaptability, flexibility, and efficiency in navigating complex environments. These ancient creatures, normally the size of a micrometer or even smaller, exhibit sophisticated locomotion and sensory abilities. By learning the decentralized control methods, body elasticity, and fluidic movements of microorganisms, researchers can develop soft robots with the multifunctionalities and the abilities to operate in confined spaces. A schematic of distribution of different microorganism bio-models used in soft-robotics research in recent years is presented in Figure 7.

Inspiration from flagellates

Flagella are slender, whip-like structures that extend from the cell bodies of various microorganisms, playing a crucial role in their mobility. These appendages are observed in both prokaryotic organisms, such as bacteria and archaea, and eukaryotic cells, including algae, protozoa, and sperm cells. The structure and operational mechanics of flagella differ markedly between prokaryotes and eukaryotes. Prokaryotic flagella, found in both bacteria and archaea, are powered by rotary motors at their base that enable high-speed rotation, facilitating movement through a propeller-like action. These motors are driven by ion flux, typically protons or sodium ions, depending on the species. In contrast, eukaryotic flagella perform a whip-like, undulatory motion driven by the sliding of microtubules within the axoneme, orchestrated by dynein molecular motors.[365]

The typical design of robots mimicking flagellates consists of a magnetic head connected to a flexible flagellum-like tail. The tail can be a continuous flexible beam-like structure made of a single material,[366,367] a rod-like structure with multiple flexible joints,[368] or a helical-shaped structure.[369] An oscillating magnetic field is applied to the robots' head, inducing a passive motion of the tail, producing net propulsion. Such a design was initiated at a centimeter scale[370] and then reduced to micrometer scale with the development of microfabrication techniques.[371] In addition to magnetic fields, acoustic wave is an alternative scheme to actuate the flexible tail attached to the robot head.[372,373] The highest propulsion speed can be observed close to the structural resonances. Light has also been reported to drive the flagellated robot with liquid-crystal films acting as active joints on the tail.[374] The waveform of this robot is more controllable but at a larger length scale and a lower speed. Such undulatory motion breaks the motion symmetry and propels the robot forward at low Reynolds numbers. This type of flagellated robot with high deformability and adaptability could perform well in complicated biomedical tasks. Figure 8A shows a light-controlled *Euglena gracilis*-inspired bio-microrobot that was designed to perform multitasks in the intestine, such as drug delivery and selective removal of diseased cells. This microrobot is able to pass through the narrow and curved microchannel and perform navigated motion precisely with the applying of periodic light illumination.[375]

Microorganisms possess flexible flagella,[380] which are critical for properly forming flagellar bundles and generating propulsion

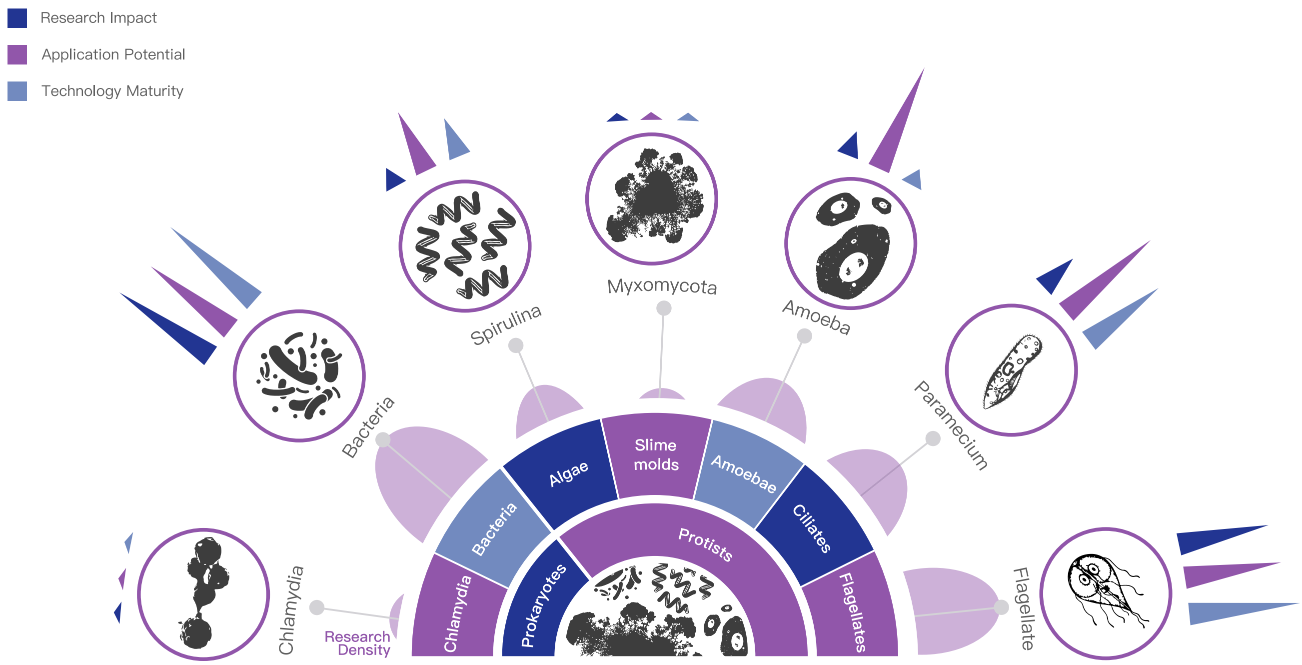

Figure 7. The distribution of microorganism models used in soft-robotics research in recent years

Typically, the size of a micrometer or even smaller, these ancient creatures exhibit sophisticated locomotion and sensory abilities. By learning the decentralized control methods, body elasticity, and fluidic movements of microorganisms, we can develop soft robots to operate in confined spaces or with swarming behavior for complex cooperative tasks or targeted delivery. Here, the area under each microorganism in the middle ring indicates the research density of a given microorganism model in current soft-robotics research, whereas the graph bars of the outer ring indicate the research impact, application potential, and technology maturity involved in using a particular microorganism bio-model for the design of soft robots at the smaller scales.

force. The flexibility in flagella also enables a "run-reverse-flick" locomotion mode, allowing bacteria to reorient. This flexible tail can be realized in microrobots by using partially dissolved and weakened silver bridges[381] or hydrogels, increasing the robots' adaptability to environments. Similar to some bacteria, such as *Escherichia coli*, that employ multiple flagella for propulsion, multiple flexible flagella can also benefit the propulsion of microrobots. Increasing the number of flagella improves swimming speeds almost linearly with the number of attached flagella.[382] Flexibility of the flagella can significantly enhance the robots' adaptability to surrounding environments (Figure 8B). The microswimmers, shown in Figure 8E, using this strategy can automatically change their helical configuration in fluids with different viscosities, thus achieving optimal propulsion.[378] The flexible body also allows the robot to pass through tortuous conduits. Micro-sized helical swimmers have been demonstrated to have great potential in drug delivery for eye surgeries[383] or clot clearance in blood vessels.[384] Apart from the magnetic field, electrical motors are also used to construct such helical-shaped robots at a larger length scale.[385,386] These robots face greater challenges in miniaturization compared to magnetic ones but can act as an ideal physical platform to study the fundamental physics behind flagellar propulsion.

Inspiration from ciliata

Motile cilia are microscopic, hair-like structures that play a crucial role in fluid transport and locomotion at low Reynolds numbers.[387] They can be found in ciliated protozoa such as *Paramecium*, *Tetrahymena*, and *Euplotes*. These tiny organelles generate net fluid flows through their asymmetric beating, which consists of a power stroke and a recovery stroke. During the power stroke, cilia extend and move rapidly, pushing and transporting the surrounding fluid. In the recovery stroke, they bend close to the cell surface and return more slowly to their initial positions. This nonreciprocal motion allows cilia to overcome the constraints of low-Reynolds-number environments, where viscous forces dominate over inertial forces.[388] The coordinated movement of multiple cilia in arrays produces metachronal waves. This collective behavior enables cilia to effectively transport fluids and propel microorganisms in viscous environments where conventional propulsion methods would be ineffective.

The locomotion of ciliates has garnered significant interest from scientists, leading to the introduction of several cilia-inspired microrobots. These artificial cilia are actuated through light,[389,390] ultrasound,[391] pressure,[392,393] magnetic fields,[376,394,395] electric fields,[51,396] pH changes,[397] or mechanical vibrations[398] and are typically larger than their biological counterparts. Among these artificial cilia, magnetic cilia are able to mimic the 3D beating of real cilia by generating conical motion[399] and can rely on their programmability to concurrently achieve 2D nonreciprocal motion of each individual cilium and the metachronal coordination of the cilia array at lengths down to 1 mm.[394] One notable research project, based on an in-depth study of *Paramecium*, designed a magnetically actuated ciliary microrobot. 3D laser lithography was used to craft the robot's body, and a special nickel and titanium bilayer was coated on the surface to achieve magnetic

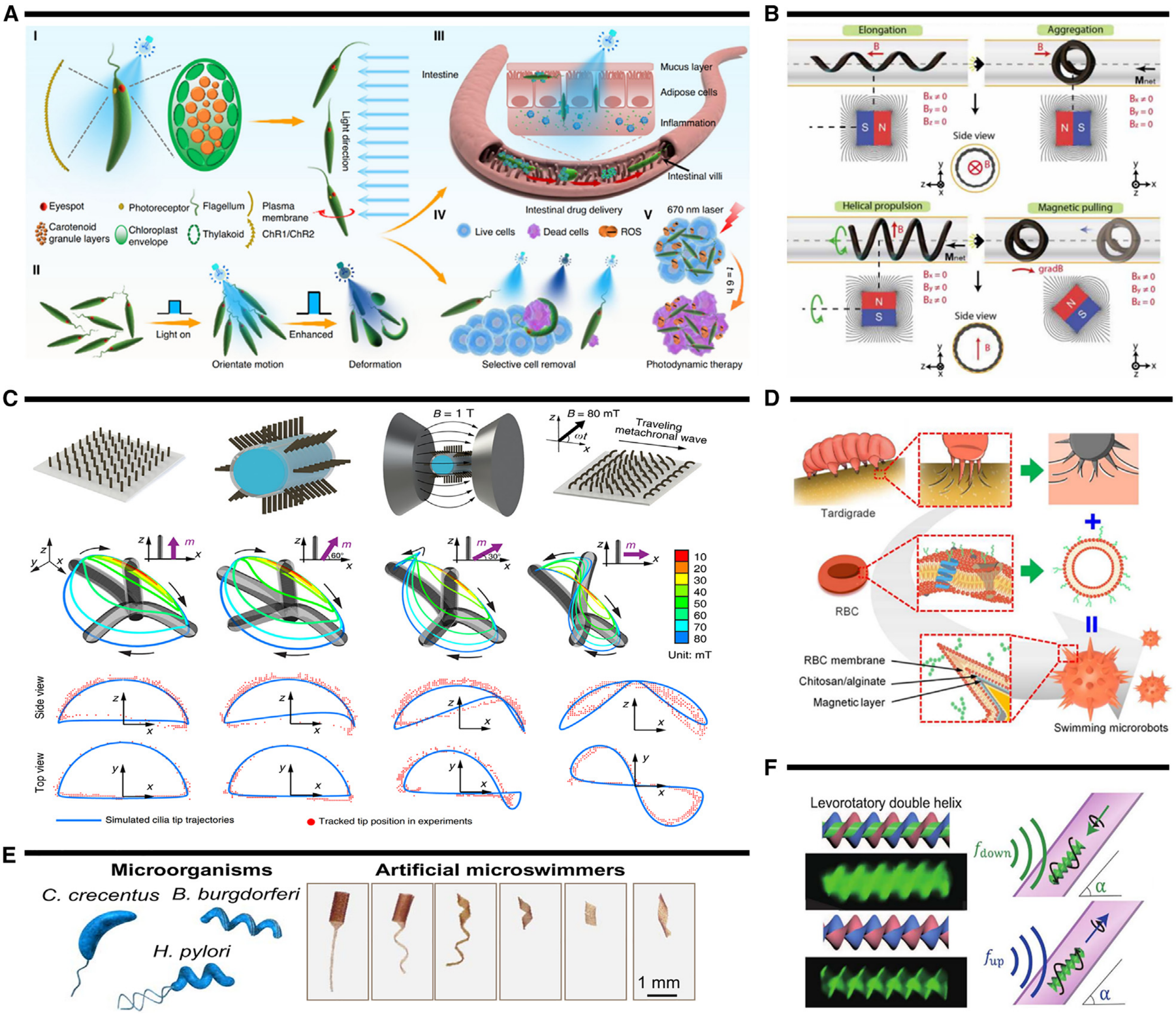

Figure 8. Soft robots developed with inspiration from microorganisms

(A) Schematic illustration of *E. gracilis*-inspired bio-microrobot and its multifunctional applications. Reprinted with permission from Xiong et al.[375] Copyright 2024, Springer Nature.

(B) Spirulina-like microrobot performs aggregation and elongation shape morphing by changing the external magnetic field. Reprinted with permission from Liu et al.[369] Copyright 2024.

(C) Cilia-inspired soft robot demonstrates rolling and crawling movements under the influence of magnetic field strength. Reprinted with permission from Gu et al.[376] Copyright 2020, Springer Nature.

(D) Tardigrade-inspired microrobot with conceptual development featuring claw engagement and biolubricated swimming capabilities. Reprinted with permission from Li et al.[377] Copyright 2023, AAAS.

(E) Flagellate-like microswimming robot with a tubular body and helical tail. Reprinted with permission from Huang et al.[378] Copyright 2019, AAAS.

(F) Spirochete-inspired microrobot with the feature of levorotatory double helix that propels in response to an external sound field. Reprinted with permission from Deng et al.[379] Copyright 2023, AAAS.

actuation and biocompatibility. A programmable magnetic field was generated to manipulate the microrobot's motion.[400] Another cilia-inspired soft robot was designed with a carpet-like shape (Figure 8C), demonstrating transport capabilities in fluid media and locomotion on solid surfaces.[376] A similar soft microrobot, but with asymmetric-structured cilia, was developed more recently. Compared to actuators with symmetric structures, it exhibited greater flexibility in locomotion and reduced complexity in magnetic control programming.[401] In addition to locomotion, the study of grasping techniques is equally important. The special claw-ground engagement mechanism of tardigrades inspired the development of swimming microrobots with the ability of superior adhesion and retention under intensive blood flow (Figure 8D). The experiment showed this microrobot achieves retention against blood flow up to 3.2 cm/s and maintains it for over 36 h.[377] Although electricity-driven cilia cannot mimic the single-cilium kinematics as well as magnetic ones, they are able to change the metachronal waves of the cilia array on demand and can be freely deployed to various static or dynamically deformable 3D surfaces for near-wall fluid manipulation.[51]

Potential applications of these artificial cilia include generating fluid flows in lab-on-a-chip systems,[395,402] transporting particles for self-cleaning of the surface,[399] and being used as scientific devices to investigate the fundamental mechanisms of cilia motion in nature.[394] Mobile miniaturized robots can also benefit from artificial cilia for propulsion. Millimeter-sized magnetic cilia can be utilized to achieve millipede-like crawling in soft millirobots.[376] Inspired by starfish larvae, ultrasound-actuated cilia bands can enable a microrobot to propel or trap particles by generating flow sources or sinks.[391] Instead of mimicking the morphology of each individual cilium, the metachronal wave induced by the collective cilia beating can be mimicked by the traveling wave deformation of the robot made of LCE.[40] Structured light patterns are projected onto the microrobots to induce localized shape changes, enabling the traveling wave deformation and robot propulsion.

The intriguing mechanism of biological cilia has also inspired researchers to develop a highly flexible sensor. A skin-like sensor, sensitive to pressure and magnetism, was fabricated using uniformly arranged magnetic cilia arrays. Cobalt particles and graphene were incorporated to achieve magnetic sensitivity and conductivity, respectively. The resistance across the sensor changed in response to variations in applied pressure or magnetic intensity.[403] Furthermore, a larger scale of cilia-inspired soft sensors was subsequently developed, enhancing the range and applicability of these devices.[404] In addition to sensing capabilities in pressure and magnetic fields, a unique design involving magnetic cilia with mushroom arrays of nanorods coated with nanoparticles enabled photocatalytic functionality.[405]

Inspiration from microalgae

Microalgae are emerging as an unconventional yet fascinating source of inspiration in biomimetic robotics. These minute organisms typically exhibit simplicity in structure, high efficiency in energy conversion, and a variety of movement types in fluidic environments, offering valuable insights for the design of soft and microrobots.

Euglenoids

One example of such microalgae is euglenoids, single-cell, soft-body microorganisms with one or more flagella that can undergo significant shape changes. Inspired by this capability, a pneumatic-driven soft robot was designed to mimic this shape-changing ability. The robot's structure resembles a hyper-elastic bellows and can be controlled using both positive and negative pneumatic pressure to achieve complex shape variations.[406]

Spirulina *microalgae*

Spirulina, known for its distinctive 3D helical structure, inspired researchers to develop a magnetic microrobot with significant commercial potential for targeted therapy. This microrobot leverages the unique characteristics of *Spirulina*, designed to release drugs controllably at specific locations through a triggered decomposition mode activated by NIR laser or adjusted pH.[407] Illustrated in Figure 8B, a *Spirulina*-shaped soft microfiberbot was developed to perform precise motion in complex neurovascular networks. This sophisticated microfiberbot can be magnetically controlled and demonstrates high steerability and reliable maneuverability.[369]

Green microalga

A cargo delivery micro-hybrid robot was developed by attaching microparticles to the surface of biocompatible green microalgae obtained from nature. These cargoes, consisting of magnetic polystyrene with multiple outer layers of positively charged polyelectrolyte, are adhered to the surface of the green microalgae through noncovalent interactions. This modification grants the green microalgae the ability to be driven magnetically.[408] Furthermore, biohybrid micromotors using algae were reported to efficiently deliver drugs into the gastrointestinal tract through oral ingestion. These algae motors maintain controllable motion within the intestinal environment for up to 12 h.[409]

Volvox *microalgae*

A specialized "Volbot" was introduced by a group of researchers. This biohybrid microrobot was developed based on natural *Volvox* microalgae, incorporating capabilities such as fluid mixing, multimode imaging, and photosynthesis. Motion control of the robot was achieved through a pre-programmed magnetic field, enabling navigation along specified routes. The study found that using red-spectrum light (approximately 650 nm) enhanced the robot's performance in areas such as motion control, bioenvironmental compatibility, and quality of photodynamic therapy.[410]

Inspiration from bacteria

Bacteria, ancient organisms that have inhabited Earth for billions of years, have evolved remarkable efficiency in propelling themselves through complex fluid environments. Researchers have extensively studied the locomotion and behavior of these unicellular microorganisms, yielding significant findings with vast potential for diverse applications.

In one study, a bacteria-based hybrid actuated microrobot was developed for targeted drug delivery to tumors. Microbeads containing drugs and magnetic particles were designed to adhere to the bacterial surface. This microrobot utilized two different actuation methods for adapting to diverse conditions: electromagnetic actuation for macro control and bacterial actuation for micro control.[411] Similarly, another soft microrobot inspired by bacteria used magnetic control to achieve precise trajectory following and perform targeted microvascular thrombolysis.[412] In order to track microrobots with complex shape and estimate the pose and depth precisely, a data-driven method in an optically manipulated microrobotics system was proposed based on a deep residual neural network with incorporation of multiple focus measurement information via Gaussian process regression (GPR).[413] In addition, spirochete bacteria, characterized with the special spiral motion, inspired Dent et al. to develop an acoustically driven helical microrobot. Figure 8F shows the structure of this microrobot, which comprises a cylindrical core and a double-helical vane. This design enabled the microrobot to be actuated by an acoustic field and shows the corkscrew-like motion. It achieved a maximum speed of 150 $\mu m/s$ under acoustic simulation, showing the potential for drug delivery in vasculature systems.[379]

Amoeba-inspired soft robots

Microorganisms like amebae and slime molds perform amoeboid locomotion.[414] This mode of locomotion primarily occurs through the extension and retraction of cytoplasmic projections known as pseudopodia. This process involves intricate biochemical interactions and physical changes within the cell's cytoskeleton. As the cell extends its pseudopodia toward a target, the rest of the cytoplasm flows into these projections, allowing the organism to move forward. The cell membrane can adhere to surfaces using these extensions, aiding in its navigation across various environments. Such fluid-like locomotion allows for significant body deformation and endows microorganisms with excellent environmental adaptability. To emulate the strengths of amoeboid locomotion in soft robots, various liquid-bodied robots have been proposed.[415]

Liquid-bodied robots are typically driven by magnetic fields, requiring the material constituting the robot bodies to be magnetoactive. One common material used is ferrofluid, in which Fe_3O_4 nanoparticles are dispersed. The control of these robots relies on heterogeneous magnetic fields, which can be generated by a permanent magnet or an array of electromagnets.[416] The magnetic potential energy well can trap the liquid-bodied robot. Moving this energy trap can move the robots across substrates, producing amoeba-like locomotion. Liquid-bodied robots can achieve unique deformation patterns such as splitting and coalescence by carefully designing the magnetic field, either through magnetic pulling forces[416] or oscillating magnetic fields.[417]

One challenge encountered by liquid-bodied robots is that their shapes are unstable and hard to maintain. Therefore, using magnetorheological fluids that have good shape-maintaining capabilities[418] or can transition from the liquid state to the solid state under a strong magnetic field[419] has been proposed. Using magnetic nanoparticle-loaded LM to construct the liquid-bodied robots is an alternative approach.[420] These robots can achieve good deformation capability after heating and can stably maintain their shapes when cooled down below the melting point. Apart from magnetic actuation, other external stimuli, such as light, can also be used to control the liquid-bodied robot.[421] Such a bimodal control scheme can realize both individual and collective control of ferrofluidic-droplet robots. In addition to dispersing magnetic particles inside the fluid, magnetic particles can also be coated outside a liquid droplet to construct a liquid-marble robot.[422,423]

Microrobots driven by live microorganisms

Biohybrid microrobots integrating live microorganisms with synthetic structures offer significant advantages due to their autonomous propulsion, adaptability, and biocompatibility. The motility of microorganisms allows these robots to propel efficiently without external power sources, enabling sustained and autonomous movement. Commonly selected microorganisms include certain species of bacteria and algae. The selection of the microorganism depends on several factors. Firstly, the mobility of the organism in the working environment must be considered. The microorganisms need not only survive in the targeted environment but also exhibit good locomotion capability. Secondly, the microorganism must coincide with the task to be conducted. For example, to deliver drugs to targeted locations, the size of the microorganisms must be small enough to penetrate the mucosal barrier. Thirdly, it is crucial to consider the pathogenicity of the microorganisms to avoid adverse immune responses.

The locomotion of these biohybrid microrobots can be guided either by external control signals or by the taxis of the microorganisms. By using a magnetic field, the propulsion direction of the biohybrid microrobots can be aligned with the field direction. Some microorganisms are naturally magnetotactic, meaning they tend to align and move along the magnetic field lines. They possess specialized organelles called magnetosomes,[196] which are intracellular chains of Fe_3O_4 nanocrystals. For microorganisms lacking inherent magnetic properties, magnetotactic behavior can be induced by culturing them in a medium containing iron oxide nanoparticles[424] allowing the cells to internalized the nanoparticles, or by letting them engulf iron-platinum-coated silica microparticles.[425] In addition to directly loading magnetic materials into the microorganisms, another approach is to attach the microorganisms to carrier structures made of magnetic material. These carriers can be artificial magnetic microtubes,[197] magnetic microparticles,[198] or even red blood cells internalized with superparamagnetic iron oxide nanoparticles (SPIONs).[426] For microorganisms expressing proteorhodopsin,[427] light intensity can be used to modulate the speed of propulsion by controlling the proton motive force. For microorganisms possessing phototaxis[428] and galvanotaxis,[429] light and electric fields can also be used for propulsion direction control. The taxis of the microorganisms enables the biohybrid microrobots to autonomously direct their locomotion without operator intervention. Bacteria with chemotaxis can move toward chemoattractants by sensing chemical[198,430–432] or pH gradients.[433] Bacteria with aerotaxis tend to move toward regions with low oxygen concentration.[434] This property is critical for targeted drug delivery to oxygen-depleted hypoxic regions in tumors.

Synthetic structures, integrated with microorganisms through physical entrapment or chemical bonds, can have different shapes, such as microbeads,[430,435,436] microtubes,[197,437,438] and microgears.[427] For structures larger than the microorganisms, multiple microorganisms can be attached. However, the collective motion of multiple microorganisms may not always positively contribute to the robot's propulsion because their movements may counteract each other unless their configurations are specifically designed.[439] These synthetic structures can be made of magnetic materials, endowing the microorganisms with magnetotaxis.[197] The structures can also be loaded with different drugs for various biomedical treatments.[426,440,441] Apart from passive drug release,[442] using stimuli-responsive materials to construct the drug carrier can enable on-demand drug release triggered by NIR light or pH changes.[443] By adopting a release mechanism,[444] drug-loaded sperm can be liberated from the synthetic structure after hitting the tumor wall. After release, the sperm can swim into the tumor and deliver its drug payload to the site.

Summary and outlook

Microorganism-inspired soft robots, mimicking the extraordinary adaptability, efficiency, and locomotion mechanisms of microorganisms, have demonstrated groundbreaking potential in navigating confined spaces, performing targeted drug delivery, and manipulating microscale environments. These innovations hold the promise to revolutionize biomedicine, enabling precise interventions and delivering therapeutics to otherwise inaccessible biological sites. Despite these advancements, several significant challenges remain, including developing advanced microfabrication techniques, addressing control complexities in dynamic and unstructured physiological environments, and ensuring the use of biocompatible and biodegradable materials. Overcoming these obstacles through interdisciplinary collaboration across robotics, materials science, and biomedical engineering will be critical to fully unlocking the transformative potential of microorganism-inspired soft robots in both research and clinical applications.

APPLICATIONS

Medical applications

Soft robots are particularly suitable for medical applications because they offer flexibility, adaptability, and biocompatibility. Compared to the cumbersome anatomical structure of traditional rigid medical robots, multimodal locomotion can be achieved by soft robots with simple, soft, and flexible bodies for reaching complex and confined targets and providing gentle and precise operations. Moreover, some soft materials, especially biohybrid soft materials, offer advantages such as biocompatibility, tunable properties, and multifunctionality.[445] These advantages make the soft robots the ideal candidates for a wide range of medical applications, including diagnosis, surgery, drug delivery, and rehabilitation.[446]

Disease diagnosis

Wang et al. used a wireless micro-soft robot for the *in situ* sensing of the physiological properties of biological tissues. A flexible implantable microrobot was designed to monitor biological tissue temperature, pH, pressure, and other physiological parameters using wireless technology. The robot was able to move freely through complex environments in the body and in close contact with tissues.[447] By integrating ferromagnetic materials and flexible structures, a robot could achieve precise shape transformation and motion control under the action of external magnetic fields. Specifically, the robot used a composite material composed of silicone and magnetic particles that could achieve bending angles of up to 180° in a 0- to 50-mT field strength range, exhibit ductility of up to 20%, and move at a speed of 5 mm/s. It was introduced to be potentially applied as an endoscope during minimally invasive surgery.[448] By assembling a microfluidic chip with a soft fiber robot, a continuous liquid biopsy for disease monitoring can be performed for a target on a sub-millimeter scale.[449] Similarly, a monolithic force-sensitive 3D microgripper can be combined with a soft microrobot to perform the precise and minimally invasive biopsy.[450] Furthermore, a novel focused ultrasound-controlled phase-transition method was used to actuate an untethered soft robot. By implementing ultrasound-induced heating to precisely control the phase-transition state of embedded fluids, high spatial resolution and Newton-level force output were achieved. This robot was designed to perform the tasks in confined space (Figure 9A). The relevant tests that were performed show promising applications in tissue biopsy, patching, and other biomedical aspects.[8]

Drug/gene delivery

The biomimetic soft microrobot has found its most impactful application in drug and gene delivery, offering precision and efficiency advantages.[454] Engineered for administration through injection or oral ingestion, these microrobots represent a shift toward minimally invasive or noninvasive delivery methods. Targeted drug-delivery therapy using these robots can significantly reduce pain, lower required dosages, and minimize side effects. Alapan et al. presented a leukocyte-inspired spherical rolling microrobot with diameter down to 3 μm. Its surface is functionalized with nickel and antibodies against cancer cells. By applying a magnetic field, the robot can be guided against the bloodstream to deliver drugs to target disease locations.[455] Servant et al. demonstrated an artificial bacterial flagellum capable of controllable swimming. These bacteria-like robots were coated with a 50-nm-thick layer of Ni for magnetic control and a 5-nm-thick layer of Ti for biocompatibility. Additionally, NIR probes (NIR-797) were introduced to enable *in vivo* optical imaging during the magnetically controlled process.[456] The distributed-force-control method for microrobot manipulation was introduced by Zhang et al., providing an intelligent contactless control strategy and showing the potential in applying to drug and gene delivery.[457] Another study focused on a soft robot with multimodal sensing capabilities for targeted drug delivery. The robot, designed based on origami techniques, integrates temperature, tactile, and electrochemical sensors and can be multidimensionally actuated by a magnetic field. This design enables precise environmental interaction and shows significant promise for biomedical applications (Figure 9B).[127]

Therapy and surgery

Minimally invasive surgery represents a promising application for many miniaturized soft robots, characterized by their small, flexible bodies and complex, programmable morphing abilities, in contrast to the rigid and inflexible nature of conventional surgical tools. Acome et al. introduced a HASEL actuator capable of muscle-like motion. This soft actuator, driven by integrated electrostatic and hydraulic forces and equipped with self-sensing capabilities, demonstrated the ability to manipulate delicate objects. It is highly regarded for potential applications in minimally invasive surgical tools such as forceps and needle holders.[147] Similarly, tendril-like and eagle-claw-shaped soft actuators, designed based on bilayer structures, exhibited comparable potential in this field. Programmable morphing was achieved by 4D printing PU filaments with varying swelling ratios.[328] A thermal-actuated soft fiberbot with a low profile was introduced to perform a high-precision minimally invasive surgery. This soft fiberbot was fabricated by highly scalable fiber drawing technology, thus having a low cost in producing and potentially enabling precise removal of cancer in challenging surgical sites.[458]

Soft robots can connect with human tissues and organs in a flexible and non-destructive way. They can enhance the functions of heart and respiration, tissue rehabilitation, and so on. Roche et al. made a soft-robotic sleeve that mimics the movements of the mammalian heart. Compressed air is pushed directly into the heart through soft pneumatic artificial muscles. As a ventricular assist device (VAD), it does not need to contact blood, providing the function of pumping blood to the failing

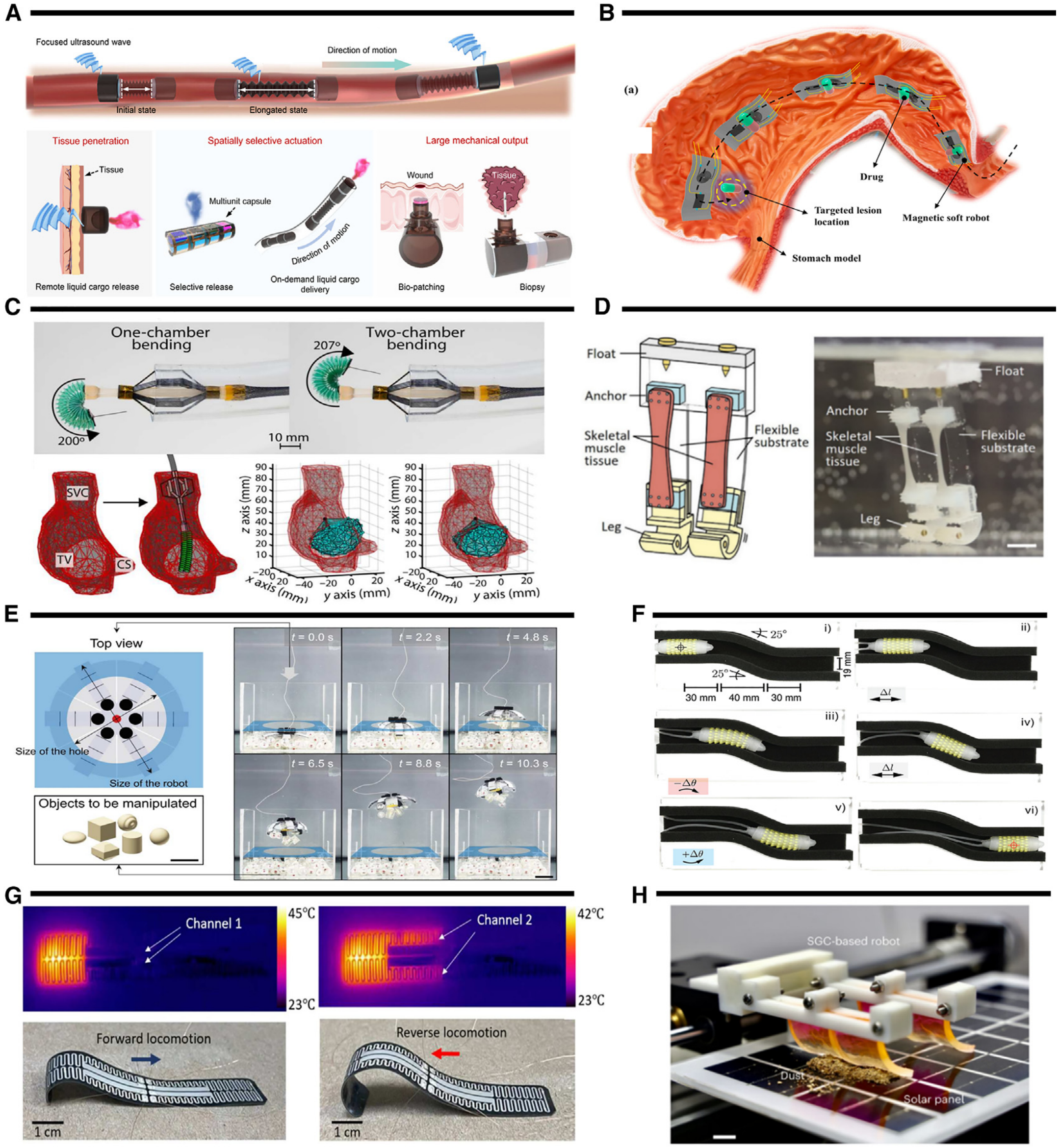

Figure 9. Applications of soft robots across various domains

(A) A soft capsule designed for cargo delivery and biopsy actuated by focused ultrasound. Reprinted with permission from Hao et al.[8] Copyright 2023, Springer Nature.

(B) A magnetic soft robot designed for drug delivery in the stomach. Reprinted with permission from Wang et al.[127] Copyright 2023, Elsevier.

(C) Millimeter-scale soft manipulator exhibits intracardiac operations in right atrium. Reprinted with permission from Rogatinsky et al.[451] Copyright 2023, AAAS.

(D) Schematic of a biohybrid bipedal soft robot designed for walking. Reprinted with permission from Kinjo et al.[208] Copyright 2023, Elsevier.

(E) A shape-adaptive soft robot designed for transporting objects of various shapes from confined spaces. Reprinted with permission from Wang et al.[1] Copyright 2023, AAAS.

(F) A crawling soft robot designed for exploration in confined and sinuous channels. Reprinted with permission from Tirado et al.[452] Copyright 2024, Wiley-VCH.

(G) A flat-shaped soft robot designed to pass through shallow and narrow gaps. Reprinted with permission from Wu et al.[2] Copyright 2023, AAAS.

(H) A stiffness-gradient soft actuator, based on the catapult principle, designed for a self-cleaning solar-power system. Reprinted with permission from Zhang et al.[453] Copyright 2024, Springer Nature.

heart.[459] Payne et al. proposed a soft-robotic VAD. Compressed air is used to drive artificial muscle actuators. It is anchored to the ventricular free wall and the inter-ventricular septum (IVS). Pressure can be applied to the left and right ventricles to help the heart contract and dilate.[460] Hu et al. used pneumatic artificial muscles. The diaphragm function is mechanically enhanced during inhalation, and it acts as an implantable ventilator to increase intake. Thus, the soft robot can assist the heart to breathe.[461] Perez-Guagnelli et al. were inspired by the anatomy of the human gastrointestinal tract to design a soft pneumatic helically interlayered actuator. Tissue-stimulation therapy is performed in multiple directions for tissue repair and regeneration.[462] This multifunctional soft-robotic platform was especially designed for minimally invasive intracardiac interventions. The robot has a collapsible design in order to navigate in narrow vascular pathways and has an expandable stabilization mechanism used to provide stability and dexterity in the heart. The robot is able to operate with other medical tools to perform procedures such as coronary sinus lead placement and tricuspid valve repair. It potentially addresses critical challenges like size constraints, motion in a beating heart, and remote operation (Figure 9C).[451]

Rehabilitation

Robotic rehabilitation systems provide the necessary strength to assist limb movement without harming patients, improving their joint and muscle function and helping them to stand up, balance, walk, and climb stairs. McKibben developed an assistive rehabilitation device based on a fluid actuator, using it to restore the movement of hands paralyzed by polio. Park et al. proposed a design-and-control method for a bionic wearable soft robot for ankle and foot rehabilitation. Flexible materials and bionic structures were used to mimic the natural movements of the human foot; precise motion control could be achieved using pneumatic and electric drive systems. It could help patients regain their ankle and foot functions, improve their range of motion, and increase their muscle strength and coordination.[463] Jiang et al. developed a fishbone-bionic soft-robotic glove for hand rehabilitation. Imitating the flexibility of fish bones, the glove enabled the natural movement of fingers and multi-dimensional control. Driven by pneumatic and servo systems, the gloves could independently control the bending and stretching of each finger, thereby providing precise rehabilitation training. The gloves demonstrated remarkable results in improving the patients' range of hand motion, muscle strength, and coordination.[464] A biohybrid bipedal robot driven by cultured skeletal muscle tissues was introduced by Kinjo et al. It was designed to mimic the human gait mechanism and is able to perform precise forward movement, stopping, and fine-tuned turning (Figure 9D). By integrating biological tissues as actuators, the robot breaks the gap between biology and robotics. More specifically, the robot with skeletal muscle tissue simulates human bipedal locomotion and provides a foundation for developing biohybrid devices to assist in retraining motor functions in patients recovering from injury or neurological disorder. Thus, it shows promising application potential in robotics rehabilitation for advancing assistive technologies and therapeutic tools.[208]

Other biomedical applications

Soft micro/nanorobots are considered suitable carriers for microparticles, designed to facilitate *in vivo* tracking imaging during targeting missions. These robots are particularly applied in medical imaging, collaborating with modalities such as MRI, X-ray computed tomography (CT), ultrasound imaging, and fluorescence imaging.[465] Yan et al. introduced a *Spirulina* biomimetic microrobot capable of both *in vivo* fluorescence imaging and MRI. These helical microrobots were dip-coated with a suspension of Fe_3O_4, a common contrast agent for MRI, providing visibility in MRI.[466] These biocompatible, soft, tiny, and controllable microrobots also hold significant potential for unique medical treatments. For instance, in addressing microvascular thrombolysis, Xie et al. introduced a magnetotactic bacteria (MTB)-inspired microrobot designed to target and dislodge blood clots. Controlled by a rotating magnetic field, this microrobot demonstrated an advantage in locomotion speed.[412] In another recent study, biomimetic helical-shaped robots showed promise for combating biofilm infections. An Fe_2O_3 helical microrobot was specifically designed for this purpose, utilizing a wobbling motion to generate high mechanical force that effectively damaged bacteria-induced biofilms. Furthermore, these Fe_2O_3 microrobots exhibited high H_2O_2 catalytic activity, enhancing bacteria eradication and resistance prevention.[467]

Logistics robots

Cargo delivery

By applying programmable stimuli, certain soft robots can be controlled to perform specific motions such as walking and swimming, demonstrating promising potential for cargo delivery in harsh and dangerous environments. Yang et al. developed a walking robot by exploring how organic polymer-crystal hybrid materials respond to changes in humidity and heat. The robot's walking ability was tested on a smooth silicon wafer, where the principle of locomotion relied on changes induced in the inner layer of the soft robot through programmed wetting-heating logic. Specifically, the inner layer contracted with increased humidity and expanded with higher temperatures. Moreover, the walking speed could be adjusted by alternating the frequency of temperature and humidity changes.[4] A light-responsive liquid-crystal polymer-based soft-robotic transporter, actuated by blue light, utilizes coordinated movement of its legs and arms to traverse a plane and perform object-picking and -releasing tasks.[468] A soft robot made of silicone elastomer embedded with hard-magnetic neodymium-iron-boron microparticles can leap over obstacles and navigate through narrow spaces under magnetic field actuation. It is also capable of grasping objects and transporting them to target locations.[47]

Soft grippers and manipulators

In the natural world, several adept hunters rely on rapid reactions and gripping abilities to capture prey. Examples include the tendril of climbing plants and the tentacle of the *Drosera* genus in the Plantae kingdom. Inspired by these natural mechanisms, researchers have developed innovative soft grippers. One such gripper is a tendril-inspired design based on a smart bilayer structure of GO and PPy. The PPy layer is patterned in strips with specific intervals, directions, and thicknesses on the GO ribbon to achieve desired curvature. This artificial tendril-like gripper can coil helically to grasp objects under high-humidity conditions ($\sim$80% RH) and release them under low-humidity conditions ($\sim$50% RH).[327] In addition to passive models, active maneuvering-controlled soft grippers have also been extensively studied. An artificial *Drosera*-inspired gripper, for instance, uses shape-morphing films (SMFs). This gripper includes artificial leaf and stem structures equipped with electrothermal heaters and four individual electrodes. By adjusting voltage distribution across these electrodes, the artificial *Drosera* can deform dynamically to actively capture objects.[341] Another study introduced an underwater soft gripper powered by HASEL actuators. The robot was designed in a jellyfish-like configuration and characterized by noise-free, energy-efficient propulsion along with versatile functionalities in confined environments (Figure 9E). This bioinspired robot can perform selective and recycling tasks in a fluidic environment.[1]

Field robots

Surveillance and reconnaissance

Biologically inspired soft robots exhibit wide ranging adaptability to complex environments and can perform dangerous and repetitive tasks, thereby reducing the chances of human exposure to dangerous environments. Owing to their small size and good maneuverability, miniature flapping-wing robots are suitable for surveillance, reconnaissance, and search-and-rescue operations in environments that are inaccessible to larger UAVs.[287] Soft robots powered by DEAs with fluid electrodes can use flexible materials to swim stealthily in water. Their translucent nature enables them to be better concealed during surveillance tasks.[145] A bionic gecko wall-climbing robot achieved efficient climbing on a smooth vertical surface. Its directional adhesion mechanism enabled the robot to remain attached at different angles, on different surface materials, and move freely; that is, it could travel freely in complex vertical environments and perform real-time monitoring and data acquisition.[239] A soft crawling robot featuring modular soft skin embedded with anisotropic bristles was introduced by Tirado et al. The robot mimics the peristaltic motion and directional friction mechanisms of earthworms, showing strong application potential in soil sensing, environmental monitoring, and sewer pipe inspections (Figure 9F).[452] Additionally, Wu et al. demonstrated a crawling soft robot powered by thermal actuation. The robot has a special thin-layer configuration, consists of LCEs and silver nanowire heaters, and demonstrated the capability of bidirectional crawling and passing through obstacles in a limited space, especially in a narrow and confined gap (Figure 9G). This advantage enables the soft crawling robot to be potentially applied in search-and-rescue operations in confined spaces.[2]

Deep-sea exploration

Bionic robotic fish have been used in missions exploring the Mariana Trench. Flexible materials can be used in extremely high-pressure environments, and high-pressure water flows can be used to generate self-charging power in deep-sea environments. The robot was capable of performing tasks at a depth of 11,000 m and was equipped with multiple sensor modules for real-time monitoring and data collection. The robot demonstrated excellent mobility and durability in the deep-sea environment, successfully collecting important data, such as temperature, pressure, and chemical composition, at the bottom of the ocean.[146] Katzschmann et al. introduced a voice-activated software robot (called Mermaid) in a deep-sea exploration application. The robot used flexible materials and bionic design and was remotely controlled by acoustic signals, which could cope with complex deep-sea environments. The hydraulically powered soft robot could remain underwater for up to 40 min; the hydraulic drive could change the swimming speed by means of tail driving (from low to high frequency). Cameras were mounted on the tip of the robot to remotely explore and capture marine life and record the environment. Underwater communication was achieved using an acoustic communication system.[182]

Robots in other fields

Various forms of soft robots show their advantages in many other fields. For example, a high-lift micro-aerial robot can be developed using muscle-like actuators. This kind of soft actuator is fabricated of multiple DEA layers along with the optimization of electrode materials. This enabled the micro-aerial robot to operate at low-voltage (500 V) while maintaining high power density (over 500 W/kg). It also showed high performance with a high lift-to-weight ratio of 3.7; position and attitude error less than 2.5 cm and 2°, respectively; and a long endurance of over 2 million cycles. This micro flying vehicle showed the ability to operate in varied environments, potentially benefiting environmental monitoring, search and rescue, and aerial imaging.[469,470] In addition to flying applications, soft-robotics technology can also be used to build a robotics jumper. A bistable soft jumper was constructed from compliant materials, embedded with a magnetic actuation mechanism. This configuration utilized snap-through instability, which allows fast transitions of energy storage and release during jumps. The soft jumper showed outstanding performance, achieving a takeoff velocity of 2 m/s and jump over 108 body heights in less than 15 ms. The robot's design is particularly suitable for monitoring the water quality and cleansing water in amphibious terrain.[471] Furthermore, soft-robotics technology can also benefit energy systems. Miao et al. introduced a 3D temporary-magnetized soft-robotics structure that can perform various controlled locomotion patterns, including local deformation, unidirectional tilting, and omnidirectional rotation by an external magnetic field. It demonstrated high mechanical robustness and capability for complex and adaptable movements. This design was implemented in a solar tracking system for energy harvesting, and it demonstrated satisfying power output and enhanced average daily power storage.[472]

Architecture

The adaptive capabilities observed in natural organisms have inspired researchers to develop soft adaptive actuators for smart building skins. Smart building skins are complex systems that integrate sophisticated mechanisms, embedded sensors, and actuators. These systems must promptly adjust to environmental changes such as ambient temperature, sunlight, humidity, and indoor ventilation.[473] Traditionally, designing such systems has been complicated and costly. Biomimetic soft actuators, however, offer a novel approach by enabling passive adaptation to environmental changes through self-morphing. For example, Reichert et al. studied the hygroscopic actuation of pine cones and developed a soft, humidity-responsive actuator for smart building skins. Several prototypes demonstrated predictable and reversible motions, exploring various functional possibilities.[474] In another approach, a biomimetic stretchable-fabric architecture skin was created using a combination of soft pneumatic grippers and SMA actuators. These smart skins could adjust the building's opening area ratio between 0% and 20%, effectively adapting to indoor ventilation requirements and climate fluctuations.[475] Zhang et al. demonstrated a soft actuator with stiffness-gradient amplified catapult mechanism (Figure 9H). By applying a material gradient from soft tips to stiff bases, the mechanism could efficiently store elastic energy and

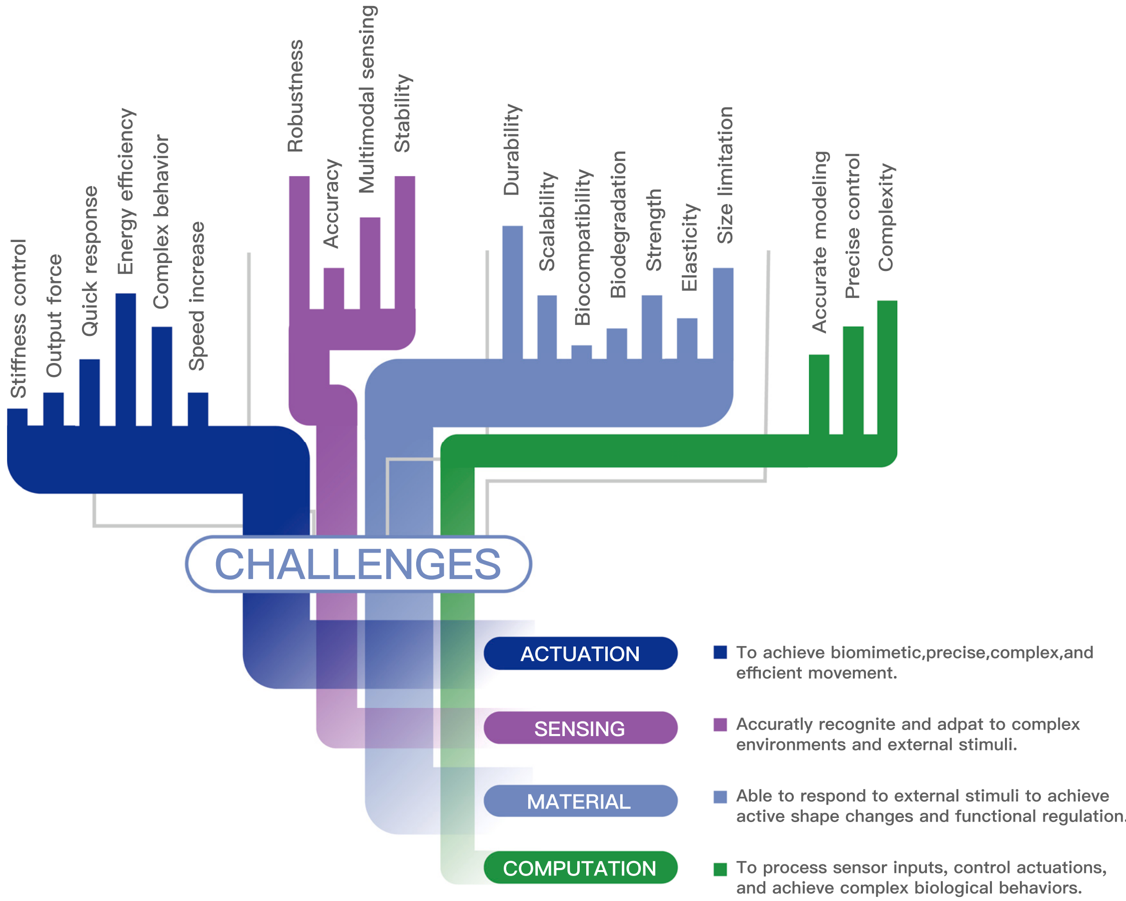

Figure 10. Future challenges facing soft robotics in areas of actuation, sensing, material, and computation, with specific issues outlined for each domain

release it at the programmed time to overcome the adhesion of microscale particles. This design demonstrates practical applications in self-cleaning systems, such as integrating this robotics system for cleaning solar panels, roofs, and windows.[453]

CHALLENGES AND FUTURE PERSPECTIVES

As the field of bioinspired soft robotics continues to advance, a plethora of challenges remain. Despite remarkable achievements to date, future progress is hindered by further obstacles in actuation, material, sensing, control, and more. This section highlights these challenges, providing a critical perspective on overcoming hurdles to fully harness the potential of biomimetic soft robotics across various applications.

In Figure 10, we present a synthesized overview of the current principal challenges of soft robotics by analyzing the recent representative review articles in this field.[17,43,44,62,96,97,476–485] The figure categorizes these challenges into four main domains: actuation, sensing, material, and computation. For each domain, we listed the challenges that are most frequently referenced. The relative impact or frequency of reference is represented visually in the figure through the height of the bars. This visual representation helps to expose the key obstacles in the development of soft robots and aims to guide future research by highlighting where focused efforts may be most beneficial.

Actuation

Recent advances in soft actuators have shown impressive capabilities in aspects such as actuation speed,[7,147,244,285,486] deformation amplitude,[50,448,487] and stiffness modulation range,[23,221,488] even exceeding the abilities of biological muscles in one or more parameters.[476,489] However, these actuators generally fall short in multifaceted performance as in biological counterparts, which adeptly balance multiple performance indicators. As such, the overall movement capabilities of soft robots are still not on a par with those observed in animals. Further, to be deployable in practical applications, especially those requiring autonomous operation in the field, soft robots must be self-contained with prolonged operational capabilities. This demands actuators that are lightweight, reasonably sized, and energy efficient. Current soft actuators, however, often necessitate bulky external devices[490] or achieve low energy efficiency,[210] posing significant hurdles to their integration into autonomous robotic systems. Furthermore, soft robots currently face difficulties in replicating the graceful and fluid movements observed in animals, and their range of motion remains relatively limited. To address this challenge, soft actuators need to produce more versatile and complex deformations.

Sensing

Biological systems rely on multimodal sensing to perceive their environment and monitor their internal states, which is crucial for different behaviors.[491–493] Similarly, bioinspired soft robots aiming to achieve comparable levels of autonomy must also be capable of sensing a wide variety of environmental and internal information. This necessitates the integration of various soft sensors within the robot's structure. Although significant advancements have been made in the development of soft electronics and sensors,[494] a major challenge remains in seamlessly integrating these sensors into the soft robot's body. Specifically, the difficulty lies in integrating the manufacturing processes of soft sensors with the robot's body construction, ensuring that the sensors are both effectively embedded and functionally cohesive within the soft-robotic system.

Material

Biological systems exhibit remarkable durability and the ability to self-repair, attributed to the resilience and self-healing capability of the biological materials. In contrast, the materials currently used in soft robotics still fall short in these aspects. Despite some pioneering advancements,[495,496] there is still a substantial gap in these two aspects necessary for long-term functionality of soft robots. Furthermore, for applications where soft robots are to be disposed of or intended for use within the human body, the materials used must also be biocompatible, or even biodegradable. Moreover, the development of new types of stimuli-responsive materials also holds great promise for the creation of new-generation high-performance actuators with a balance of flexibility and mechanical strength. In addition, it is necessary to explore the potential of smart robotic materials that integrate sensing, actuation, computation, and communication. The aim is to emulate biological systems by tightly coupling physical properties with distributed intelligence, enabling multifunctional and environmental adaptive abilities.[497]

Control

The control of soft robots presents significant challenges due to several key factors. First, while the inherent flexibility of soft robots offers numerous advantages, it also introduces a large number of DOFs, both passive and active. This high DOF count complicates the modeling and control of soft robots, making it difficult to develop effective model-based control algorithms. The large number of DOFs also exacerbates computational difficulties, posing significant challenges in achieving real-time control.[498] Additionally, the nonlinear stress-strain relationships inherent to the soft materials building these robots as well as the large and continuous body deformations lead to complex and highly nonlinear dynamics. These dynamics are notoriously difficult for conventional control algorithms to handle.[499,500] Furthermore, the performance of soft robots, particularly in terms of locomotion, is heavily influenced by the external environment. The interaction between the robot and its environment involves multi-physics coupling. This interaction makes the dynamic system not only hard to predict but also challenging to perceive accurately, adding another layer of nonlinearity and uncertainty to the control problem. To leverage these control problems of soft robots, further efforts are required. For example, there is potential to develop well-designed morphological computation to enable soft robots to handle complex tasks with simpler control strategies. In addition, morphological computation could integrate sensing directly into the body design, thus turning the morphology into a dynamic filter for external signals.[501]

Scalability

A significant challenge in advancing soft robotics is the upscaling of bioinspired soft robots for industrial applications. While these robots have demonstrated remarkable capabilities in laboratory settings, several material and design limitations hinder their transition to large-scale practical use. While flexible and adaptable, soft materials such as silicones, elastomers, and hydrogels often lack the mechanical robustness required for industrial environments. In such settings, these materials are exposed to significant mechanical stresses, wear, and harsh chemicals, leading to fatigue and degradation over time, which restricts their applicability in scenarios demanding long-term reliability.[210,502] Moreover, the intricate designs and fabrication techniques employed at small scales for soft robots pose additional challenges when scaled for industrial production. Manufacturing methods, such as 3D printing and laser lithography, commonly used in laboratory prototypes, are often too time-intensive and cost-prohibitive for mass production.[503] Furthermore, integrating soft robots into established industrial systems is complicated by their compliant nature, which frequently requires customized equipment or modifications to standard machinery to accommodate their unique structural and operational characteristics.[504]

Current research tackles these challenges by developing advanced materials with enhanced durability and improved mechanical properties, such as composite elastomers and reinforced hydrogels. These materials aim to retain the desirable flexibility of traditional soft-robotics materials and offer greater resistance to industrial wear and environmental factors. In addition, there is a strong focus on designing simplified and modular soft robots that can be more easily manufactured using scalable methods like injection molding and roll-to-roll processing, which are better suited for large-scale production.[505] In parallel, researchers are also working on refining control algorithms and developing standardized interfaces to facilitate the seamless integration of soft robots into existing industrial workflows. By ensuring that soft-robotics systems can communicate and function effectively within current automated environments, these efforts aim to make soft robots more practical and adaptable for widespread industrial applications. While significant progress has been made, bridging the gap between laboratory demonstrations and real-world industrial implementation remains a complex challenge. Ongoing interdisciplinary research in materials science, robotics engineering, and manufacturing processes is essential to overcome these barriers and unlock the potential of soft robotics in industrial and large-scale settings.

Cross-scale embodiment

On the micro/nano scale, soft robots are primarily designed for applications such as drug delivery and minimally invasive

Table 2. Comparison between bioinspired and biohybrid soft robots

Aspect	Bioinspired soft robot Advantages	Bioinspired soft robot Disadvantages	Biohybrid soft robot Advantages	Biohybrid soft robot Disadvantages
Materials	● synthetic materials are predictable and controllable ● durable and resistant to harsh environments ● compatible with existing fabrication processes	● many synthetic materials face issues with biocompatibility and biodegradability ● not self-healing or regenerative	● incorporates living cells or tissues for bio-functionality ● self-healing or regenerative abilities ● enhanced biocompatibility	● difficult to sustain the vitality of biological materials. ● challenging in fabrication and integration ● hard to use in harsh environment
Motion and control	● consistent and predictable behavior over time ● flexibility to employ motion strategies beyond biological systems ● better controllability	● not fully replicating or mimicking complex biological processes	● high adaptability and responsiveness to stimuli ● potential for autonomous behavior (e.g., taxis)	● difficulty in precise control ● performance depends on the viability of biological components
Applications	● broad range of uses (industrial, medical devices, exploration) ● easier scalability and mass production	● may struggle with applications requiring bio-functionality or biocompatibility	● ideal for biomedical applications (integration with biological tissues, tissue engineering)	● does not fit harsh environment ● require specialized handling and storage conditions

surgery, with stringent development standards. However, several obstacles hinder their practical suitability. Firstly, the limited availability of biocompatible particles and materials delays the practical application speed of micro/nano soft robots. Therefore, state-of-the-art biocompatible materials need to be investigated. Secondly, to perform complex interventional tasks, precise control of actuation is crucial. Future studies may focus on hybrid or multi-method actuation techniques coupled with sophisticated control algorithms. Moreover, specific challenges arise when deploying these robots in surgical environments. For instance, the drawback of response time, stiffness, and biocompatibility poses feasibility issues, despite their potential importance in numerous surgeries. Hence, innovative actuation methods must be further researched to address these specific challenges and enhance practicality and usability.

The path toward mature, readily available bioinspired and biohybrid soft robots requires pushing the boundaries of different technologies and tackling the fundamental challenges in respective science and engineering disciplines. To overcome these challenges and propel soft robotics toward maturity, several key areas demand focused research and development. These include new materials and fabrication techniques to address the aforementioned challenges, also by leveraging parallel advances in multi-material additive manufacturing to facilitate the creation of complex structural designs and embodiment schemes with novel sensing and actuation schemes. We need to challenge our traditional way of thinking in sensing, actuation, and control for robotics and inspire the development of "a new generation of robots that are multi-functional, power-efficient, compliant, and autonomous in ways akin to biological organisms."[506] Understandably, these robots would be difficult to characterize by traditional analytical models. It is natural in a young discipline to proceed by trial and error, and this approach has been particularly successful in soft robotics so far, bringing progress at a fast pace. Despite such progress, the lack of complete models for design and control sometimes hinders wider-scale adoption with repeatable and standardized performances, especially for safety-critical applications such as minimally invasive surgery. A wider adoption of computational modeling in soft robotics provides a way of progressing to a biology- and physics-informed discipline.[507] Therefore, new modeling schemes, particularly with those using machine-learning methods empowered by explainable artificial intelligence (AI) would be a worthy avenue to pursue. It is also necessary to establish standardized testing and evaluation protocols for these robots, and considering factors like actuation performance, sensitivity, accuracy, repeatability, and long-term stability is essential for benchmarking performance and driving innovation. Addressing these challenges will require collaborative efforts across disciplines, bridging materials science, mechanical engineering, electrical engineering, and computer science. As soft sensing technology matures, it will unlock the full potential of soft robotics, enabling the creation of adaptable machines capable of interacting safely and effectively with the world around us.

CONCLUSIONS

The development of soft robots by drawing inspiration from creatures in nature and imitating the structure, function, and processes of organisms shows considerable potential and can resolve many challenges and unmet demands that exist in the field of robotics. The future of bioinspired soft robotics lies in advancing beyond merely replicating the outer morphology and general motion of biological systems. To truly mimic the complexity and functionality of living organisms, future soft robots will need to emulate the underlying structures and working principles of these systems in much greater detail. This includes the arrangement of actuators, the forms of actuation, the proper placement of sensors, the types of sensing mechanisms employed, and the development of sophisticated control strategies that mirror the intricate coordination seen in animals. Furthermore, these robots should be designed to mimic biological systems across multiple hierarchical levels, reflecting the way living organisms operate as integrated, multiscale systems.

Additionally, directly integrating biological components into robotic systems can create soft robots that better mimic their biological counterparts and offer advantages that are not achievable with synthetic components (Table 2). Compared to synthetic soft robots, biohybrid soft robots can leverage the living cells or tissues constituting their bodies to achieve self-healing and regenerative abilities, enhance biocompatibility, increase adaptability and responsiveness to stimuli, and potentially exhibit autonomous behaviors. However, many drawbacks still exist, including the challenges in fabrication and integration, poor endurance in harsh environments, difficulty in precise control, and variable performance.

With the advancements in actuation, sensing, materials, and control, future bioinspired and biohybrid soft robots will be better equipped to perform a wide range of real-world applications. These could include tasks in medical care, where safety and precision are paramount; housekeeping and personal assistance, where effective and safe interaction with humans is crucial; and surveillance or exploration in challenging environments, where resilience and locomotion performance are critical. As these capabilities are realized, bioinspired soft robots will increasingly become indispensable tools in our daily lives.

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AUTHOR CONTRIBUTIONS

Conceptualization, G.-Z.Y., Z.C., and J.C.; writing – original draft, Z.C., J.C., S.J., H.-Y.K., M.L.P., and Z.R.; writing – review & editing, G.-Z.Y., Z.C., H.-Y.K., C.L., M.S., and R.J.F.; supervision, G.-Z.Y.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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