Review

Biology and bioinspiration of soft robotics: Actuation, sensing, and system integration

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SUMMARY

Organisms in nature grow with senses, nervous, and actuation systems coordinated in ingenious ways to sustain metabolism and other essential life activities. The understanding of biological structures and functions guide the construction of soft robotics with unprecedented performances. However, despite the progress in soft robotics, there still remains a big gap between man-made soft robotics and natural lives in terms of autonomy, adaptability, self-repair, durability, energy efficiency, etc. Here, the actuation and sensing strategies in the natural biological world are summarized along with their man-made counterparts applied in soft robotics. The development trends of bioinspired soft robotics toward closed loop and embodiment are proposed. Challenges for obtaining autonomous soft robotics similar to natural organisms are outlined to provide a perspective in this field.

INTRODUCTION

In the past, making robots like "ironman" with superior properties in terms of high-temperature resistance, superior strength, extreme environmental tolerance, fast speed, good precision, high controllability, and low cost has been the goal of robotics (Figure 1 left) (Kuindersma et al., 2016; Nelson et al., 2017). Although great progress has been made, their performances are still not satisfactory. For instance, motion agility and versatility are still inferior to those of a cat. Additionally, the performance in terms of energy efficiency, adaptability, self-repair, durability, and other aspects is far inferior to those of natural organisms.

Soft robotics expands the scope of research studies in robotics to serve new needs linked to adaptation and safety (Coyle et al., 2018; Kim et al., 2013; Martinez et al., 2013; Pfeifer et al., 2012; Whitesides, 2018).With these goals in mind, many efforts have been devoted to adding sensation and computation skills to soft robotics without hindering their agility (Shih et al., 2020; Thuruthel et al., 2019; Wang et al., 2018b, 2021). To obtain autonomy in dynamic environment, closed-loop controls are necessary to incorporate for self-correction of errors and smart human-robot interactions (Figure 1 right) (Kaspar et al., 2021). Living organisms possess the most ingenious and efficient closed-loop controls in the world. Their behaviors are not accomplished by a single organ but rather by rational and well-organized cooperation of multiple biofunctional modules (Mykles et al., 2010). The muscles (actuation), skin (sensing), neural networks, and brain (computation) are seamlessly integrated, conferring them intrinsic adaptability, self-healing, robustness, versatility, and other properties that cannot be surpassed by conventional robots (Figure 1 middle) (Broom and Broom, 1981; Lehman, 2013). Facilitated by emerging technologies (e.g., additive manufacturing), abundant research studies have been conducted on bioinspired soft robotics (Coyle et al., 2018; Ilami et al., 2021; Kovač, 2014). Despite remarkable progress of these years, a big gap between "bioinspired soft robotics" and natural organisms still exists.

Living organisms depend on real-time and stored information to react, while soft robotics often suffer from nontrivial integration with actuators, sensors, and controllers. To achieve perception in soft robotics, important issues regard the development of soft actuators, stretchable sensors, and embedded electronics. Over the past few decades, several reviews dealing with the recent development of soft robotics have been reported. Such reviews have mainly focused on materials (Appiah et al., 2019; Majidi, 2018; Miriyev et al., 2017; Truby and Lewis, 2016), manufacturing techniques (Kuang et al., 2019; Rus and Tolley, 2018; Schmitt et al., 2018; Wallin et al., 2018), and applications (Bao et al., 2018; Cianchetti et al., 2018; Runciman et al., 2019; Sitti, 2018). However, comprehensive reviews dealing with biologically inspired and integrated soft robotics are still lacking. In this review, an overview is provided to fill the gap. A transition from

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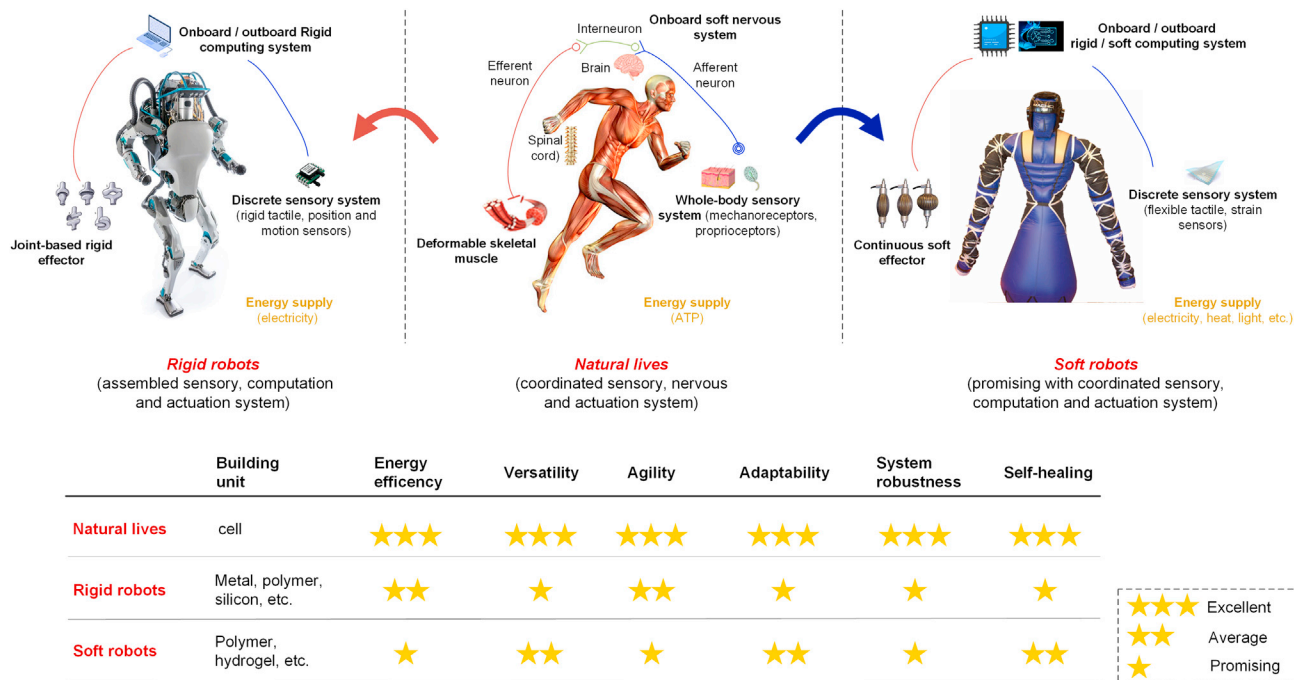
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	Building unit	Energy efficency	Versatility	Agility	Adaptability	System robustness	Self-healing
Natural lives	cell	★★★	★★★	★★★	★★★	★★★	★★★
Rigid robots	Metal, polymer, silicon, etc.	★★	★	★★	★	★	★
Soft robots	Polymer, hydrogel, etc.	★	★★	★	★★	★	★★

★★★ Excellent
★★ Average
★ Promising

Figure 1. Schematic comparison of the composition and performance of natural lives, rigid robots, and soft robots

biological mechanisms to bioinspired soft actuators and sensors is first performed, and the four main integration trends of soft robotics are then provided to point out the future for integrated soft robotics.

ACTUATION AND MECHANORECEPTION IN BIOLOGICAL WORLD AND BIOINSPIRED APPLICATIONS

The concept of "Nature as model, Nature as measure, and Nature as mentor" was proposed by Benyus at the start of her book (Dicks, 2016). In nature, animals and plants were born with integrated actuation and perception that can be reconfigured to cope with different environments using minimal energy. Nature relies on simple and smart mechanisms and a small set of nonhazardous building blocks to form diverse structures. In this section, actuation and sensing strategies in the biological world and their bioinspired applications are provided.

Actuation type in the plant system is divided into active and passive actuation (Figure 2, leftmost two columns). Active systems (biochemical-energy-based actuation) activate and control the response by moving ions and altering the permeability of membranes. Passive systems (humidity-driven actuation) are mainly based on dead tissues designed to undergo predetermined changes under environmental conditions. Actuation in the animal system adopts a different classification method, which is based on structural designs (muscles and hydrostatic skeleton) and specific functions (locomotion and manipulation) (Figure 2, middle two columns). For mechanoreception in sensing, the motifs can be broken into structural (fingerprint, interlocked, porous, whiskers, hierarchical, and crack structures) and functional categories (mechanoreceptors, ion channels, and sensory neuron systems) (Figure 2, rightmost two columns).

Actuation in biological world and bioinspired applications
Soft actuation strategies of the plant system
In plants, cellulose or chitin in cell walls evolves to form various structural features to enable uniform hygroscopic actuation for sophisticated movements. To enable uniform hygroscopic actuation with desired movements, plants have evolved delicate strategies, such as cellular organization, anisotropic orientation, mechanical instability, etc.

The cellular organization is one of the most commonly used measures to facilitate movement, which contains the cellular distribution, density, and morphology (Figure 3A). For instance, the pulvinus rapid bending in
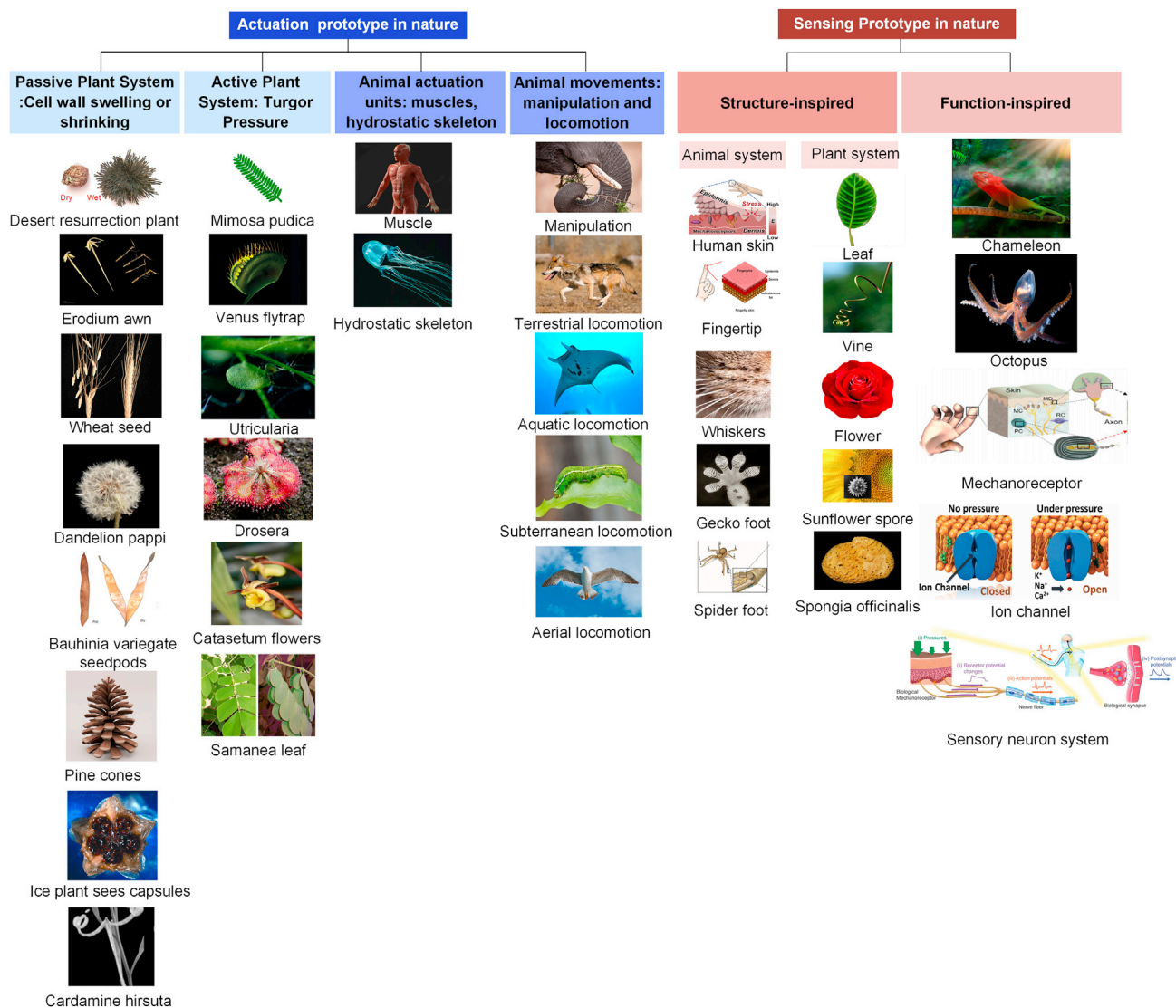
Figure 2. Overview of the biological actuation and sensing motifs in nature

Mimosa pudica originates from the different turgor pressure between motor cells at the lower and upper epidermis (Guo et al., 2015). Besides, *Selaginella lepidophylla*, found in the Chihuahuan Desert, curl their stems upon dehydration to form a sphere, which is caused by the variation in cell density of the abaxial and adaxial zones of the stem tissue (Rafsanjani et al., 2015). To enable seed dispersal, the keel cells of the ice plant seed capsule have evolved ellipsoid-hexagonal shape to unfold the capsule (Guiducci et al., 2016).

Plant cell walls are fibrous consisting of layers of stiff cellulose fibers cross-linked by polysaccharides (Cosgrove, 2005; Tuchman et al., 2020). These fibers impart anisotropy to the cell wall and transform osmotic pressurization and hygroscopic swelling into sophisticated deformations (Figure 3B). For instance, the scale of the pine cone consists of orthogonal cellulose fibers to achieve reciprocal bending with the ambient humidity cycles (Reyssat and Mahadevan, 2009). Besides, the anisotropic orientation of cellulose fibers enables the self-burial of seeds. *Erodium cicutariu* presents a self-burial movement when hydrated owing to tilted helical fiber (Rus and Tolley, 2015).

Osmotic pressure and the rate of water diffusion by hygroscopic expansion/contraction limit the response time of natural organisms. Plants have evolved several physiological features such as bistable snap-through, fracture, and water cavitation to amplify the speed and magnitude of locomotion
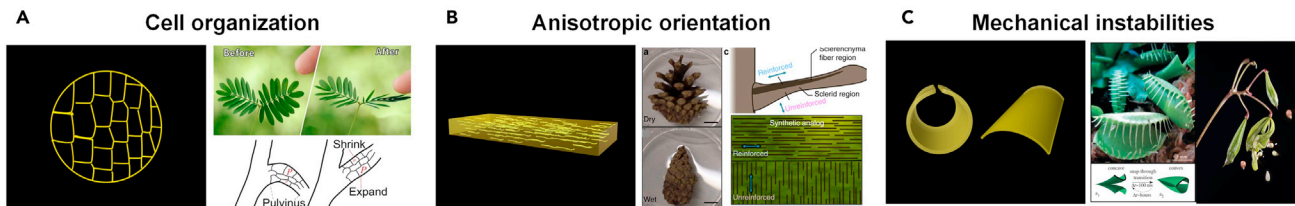
Figure 3. Overview of actuation structural/functional motifs (left) and prototypes (right) in the plant system
(A) Cell organization. Adapted with permission from Guo et al., 2015. Copyright 2015, The Royal Society.
(B) Anisotropic orientation. Adapted with permission from Erb, et al., 2013. Copyright 2013, Springer Nature.
(C) Mechanical instability. Adapted with permission from Guo et al., 2015. Copyright 2015, The Royal Society.

(Figure 3C). For example, the Venus flytrap plant can maintain at its stable equilibrium without requiring pressure supply and achieve impulsive and reversible deformation under minimum pressure changes (Forterre et al., 2005). *Impatiens glandulifera* relies on fracture mechanics to spread seeds up to two meters away from the mother plant via explosive dehiscence (Deegan, 2012). Different from bistable snap-through, fracture is a one-shot process and usually undergoes a cascade of changes of elastic energy (Hayashi et al., 2009).

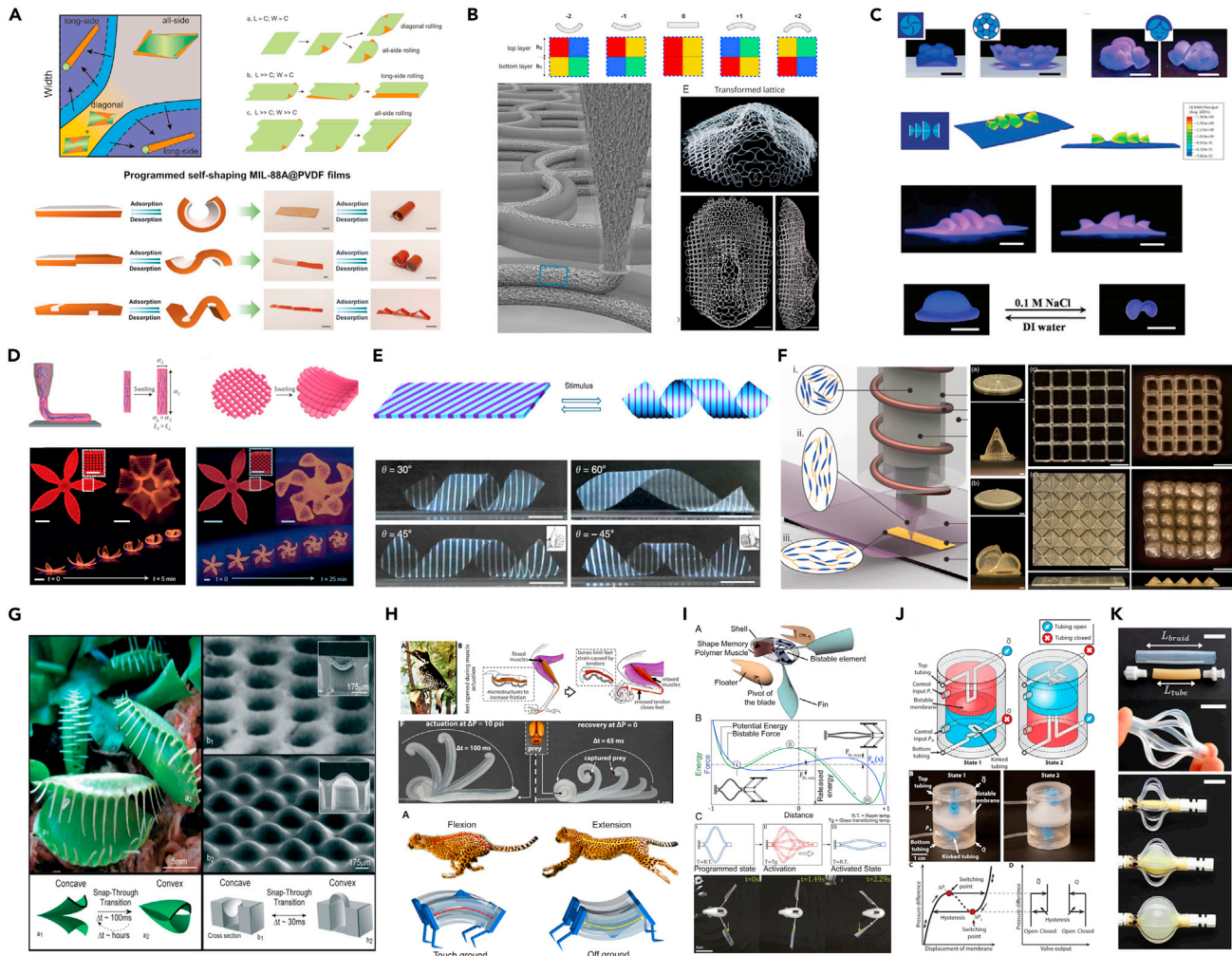*Soft actuation inspired by plant actuation*

In plant systems, the most important actuation strategy is the nonuniform stress caused by structural inhomogeneity. Similar to cellular organization and cellulose fiber orientations determining shape changes, the spatial distributions and orientations of the synthetic building blocks determine the deformations.

The realization of nonuniform stress by manmade technologies usually requires stimuli-responsive materials coupled with an innovative structural design (Hu et al., 2020; Zhao et al., 2019). The uniform stress could be introduced by the in-depth and in-plane inhomogeneity. This can be realized by multilayer structures with mismatch strains among different layers or within one layer (Liu et al., 2016). Bilayer is a simplified model of cellular organization in plant systems, in which one layer is made of responsive material and the other is passive material. The passive layer acts similar to a kinematic constraint, leading to folding due to the relaxation of internal stresses by mismatched thermal expansion, swellability, etc. For instance, Maspoch et al. developed multiaxial actuated films with reversible 2D-to-3D transformations by fabricating patterns of passive nonfolding domains and active self-folding domains (Figure 4A) (Troyano et al., 2019). Lewis et al. created multiplexed bilayer ribs composed of four materials with tunable cross-link density and anisotropic filler. These materials enabled complex shape-morphing architectures (e.g., human face) in response to temperature change (Figure 4B) (Boley et al., 2019). Using similar principles, many studies have recently explored the gradient structure enabled by cross-linking density (Wu et al., 2018a, 2018b), print speed (Ren et al., 2020), print temperature (Zhang et al., 2019a, 2019b, 2019c), and gradient 3D printing (Song et al., 2020). For example, Huang et al. used a digital projector to dynamically and spatially control light to initiate polymerization and form different conversions and cross-linking densities over poly hydrogel (Figure 4C) (Huang et al., 2017). Upon swelling, the printed hydrogel converts into 3D shapes by the inhomogeneous swelling ratio and mechanical properties.

The orientation of celluloses is another common method to achieve complex movement in the plant kingdom and has been widely used in soft actuation. Lewis et al. developed localized composite hydrogels with anisotropic swelling by aligning cellulose fibrils along prescribed four-dimensional printing pathways (Figure 4D) (Sydney Gladman et al., 2016). Kumacheva et al. fabricated twisted single-layer material with bending behaviors made of stripes with alternating chemical compositions (Figure 4E) (Wu et al., 2013). The mesogen domains of liquid crystal elastomers can be oriented during the printing progress as the anisotropic filler to generate multiuple reversible deformations, which have been widely investigated in recent years (Figure 4F) (Kotikian et al., 2018; Ren et al., 2020).

Another strategy based on mechanical instability exists not only in the plant but also in animal systems. Those structures undergo large amplitudes of displacements and strokes to suddenly release stored elastic energy (Oliver et al., 2016). Crosby et al. initially presented a simple, robust, and biomimetic responsive surface based on an array of microlens shells snapping from concave to convex under critical stress

Figure 4. Soft actuators inspired by plant actuation systems

(A) Shape morphing enabled by local material distribution in bilayers. Adapted with permission from Troyano et al., 2019. Copyright 2019, John Wiley and Sons.

(B) 3D lattices enabled by four different bilayer material combinations. Adapted with permission from Boley et al., 2019. Copyright 2019, The National Academy of Sciences (NAS).

(C) Popping-up behaviors enabled by different cross-linking densities in local regions with the same material. Adapted with permission from Huang et al., 2017. Copyright 2017, John Wiley and Sons.

(D) Programmed deformations enabled by localized and anisotropic cellulose fibrils. Adapted with permission from Sydney Gladman et al., 2016. Copyright 2016, Springer Nature.

(E) Twisting behaviors enabled by alternating chemical compositions. Adapted with permission from Wu et al., 2013. Copyright 2013, Springer Nature.

(F) In-plane and out-of-plane reversible deformations enabled by aligned mesogen domains. Adapted with permission from Kotikian et al., 2018. Copyright 2018, John Wiley and Sons.

(G) Snapping from concave to convex enabled by mechanical instabilities. Adapted with permission from Holmes and Crosby, 2007. Copyright 2007, John Wiley and Sons.

(H) Fast release in fully soft and hybrid pneumatic actuators enabled by stored elastic energy. Adapted with permission from Pal et al., 2020 and Tang et al., 2020. Copyright 2020, John Wiley and Sons; AAAS.

(I) Bistable shape memory polymer "muscles" enabled by bistable structures. Adapted with permission from Chen et al., 2018b. Copyright 2018, The NAS.

(J) Snap-through instability of a hemispherical membrane enabled by bistable structures. Adapted with permission from Preston et al., 2019. Copyright 2019, The NAS.

(K) Fast actuation of a soft fluidic actuator enabled by bistable structures. Adapted with permission from Overvelde et al., 2015. Copyright 2015, The NAS.

development in the shell structure (Figure 4G) (Holmes and Crosby, 2007). The principle is commonly used in soft actuators requiring fast actuation and massive stroke. For example, Yin et al. and Martinez et al. exploited stored elastic energy for enabling high speed and high force in fully soft and hybrid pneumatic
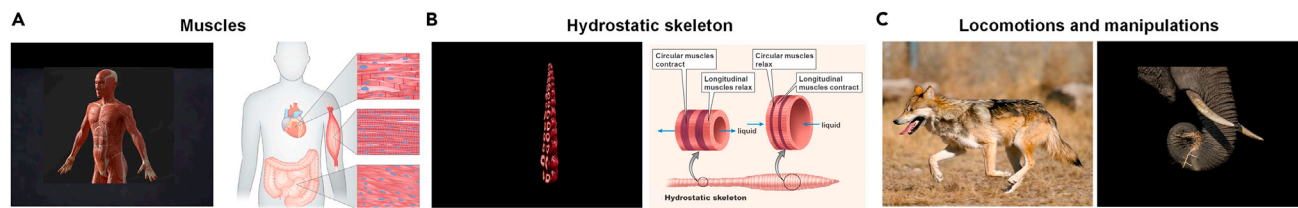
Figure 5. Overview of actuation structural/functional motifs (left) and prototypes (right) in the animal system
(A–C) (A) muscles, (B) hydrostatic skeleton, (C) locomotion and manipulation.

actuators (Figure 4H) (Pal et al., 2020; Tang et al., 2020). Further research studies utilize this method in untethered directional propulsion, enabling it to respond to temperature changes using bistable shape memory polymer (SMP) "muscles" (Figure 4I) (Chen et al., 2018b). Besides, bistable valves relying on snapthrough instability of hemispherical membrane were fabricated for autonomous control of airflow (Figure 4J) (Preston et al., 2019; Rothemund, et al., 2018). Soft fluidic actuators with amplified responses were proposed by harnessing snap-through instabilities at a constant volume to generate large motion, high forces, and fast actuation at a constant volume (Figure 4K) (Overvelde et al., 2015).

Soft actuation strategies of the animal system

Animals have more movement freedom than plant systems because their actuation units are composed of muscles assisted with skeletons or fluids (hydrostatic muscles) to facilitate manipulation and locomotion. As a result, actuation in the animal system is characterized by high flexibility, superior redundancy, and a large load-to-weight ratio. However, the difficulty in drawing principles from the extremely complicated actuating systems renders high-level animal functions difficult to produce in artificial soft actuators. Here, a brief introduction regarding biological actuation structures (muscles and hydrostatic skeletons) and various functions (manipulations and locomotion) in the existing animal world is discussed to gain further insights.

In most animals, muscles assisted with skeletons are an overwhelmingly common tool and direct means of actuation. Upon ignition by neuronal signals, muscles convert chemical energy produced through hydrolytic ATP > ADP synthesis into mechanical energy. This takes place by using reversible hydrogen bonding between myosin and actin sliding across each other during muscle contraction. Such microscopic action translates into macroscale motion through complex hierarchical structures. Muscles are good examples of linear molecular stepping motors controlled by the nervous system, capable of contracting by 20% relative to their resting lengths. A muscle work density can reach 40 kJ/m^3, with a life cycle of more than 10^9 and efficiency up to 40% (Bottinelli and Reggiani, 2000) (Figure 5A). Unlike most artificial muscles, muscles contain sufficient ATP with tens of contraction/relaxation cycles (Yamada, 2017).

In the animal world, a wide range of animals lacks skeletal supports, such as vertebrates and arthropods. These animals utilize hydrostatic skeleton to exert forces (Kier, 2012; Liu et al., 2019). Hydrostatic skeleton is a fluid mechanism by which contractile elements may be antagonized. A hydrostatic skeleton includes a liquid-filled cavity surrounded by a tissue-fibers-reinforced muscular wall (Figure 5B). For instance, spiders use hydraulic force instead of muscle to extend their legs during locomotion. Starfish uses its vascular system and tube feet to walk. Other life forms such as mollusks, bivalves, and worms utilize hydraulic transmission (Kier, 2012). The animals with hydrostatic skeletons dominated by animals is in small volume, and large soft invertebrates live either in water (squid and jellyfish) or underground (giant earthworms) (Kim et al., 2013). Soft tissues actuated by hydrostatic skeletons are often unable to exert large inertial forces and fast speed when loaded with heavy forces. However, body parts may move quickly under the pressure of low loads. For instance, low-aspect-ratio arms of octopuses can extend quickly, and caterpillars can capture their prey within a few hundred milliseconds.

Manipulation and locomotion are routine activities undertaken by animals to find food and avoid predators, etc (Figure 5C). The ontology of animals under specific environments, food sources, and ancestry all constrain locomotive capability (Vincent, 2009). For example, a high-speed chase is a desirable trait of hunters such as a lion, and therefore, it has evolved to possess very high acceleration over short distances. By comparison, the tortoise does not have to chase down its food, and thus, it has evolved to resist predatory attacks through armor rather than avoidance. The speed at which an animal travels and energy

cost for traveling depend on the mode of locomotion and size (Peyré-Tartaruga and Coertjens, 2018). Because locomotion is a major metabolic sink in animals, the least energy principle is highly applicable to the study of locomotion. Larger animals commonly travel faster than small ones for each mode of loco-motion. They also use less power per unit of body mass. Overall, locomotion is optimized for efficiency all the time. Hence, the locomotion strategies of the biological world (geometry, structures, locomotion mode, etc.) can be used for designing more efficient soft actuators that suit various applications.
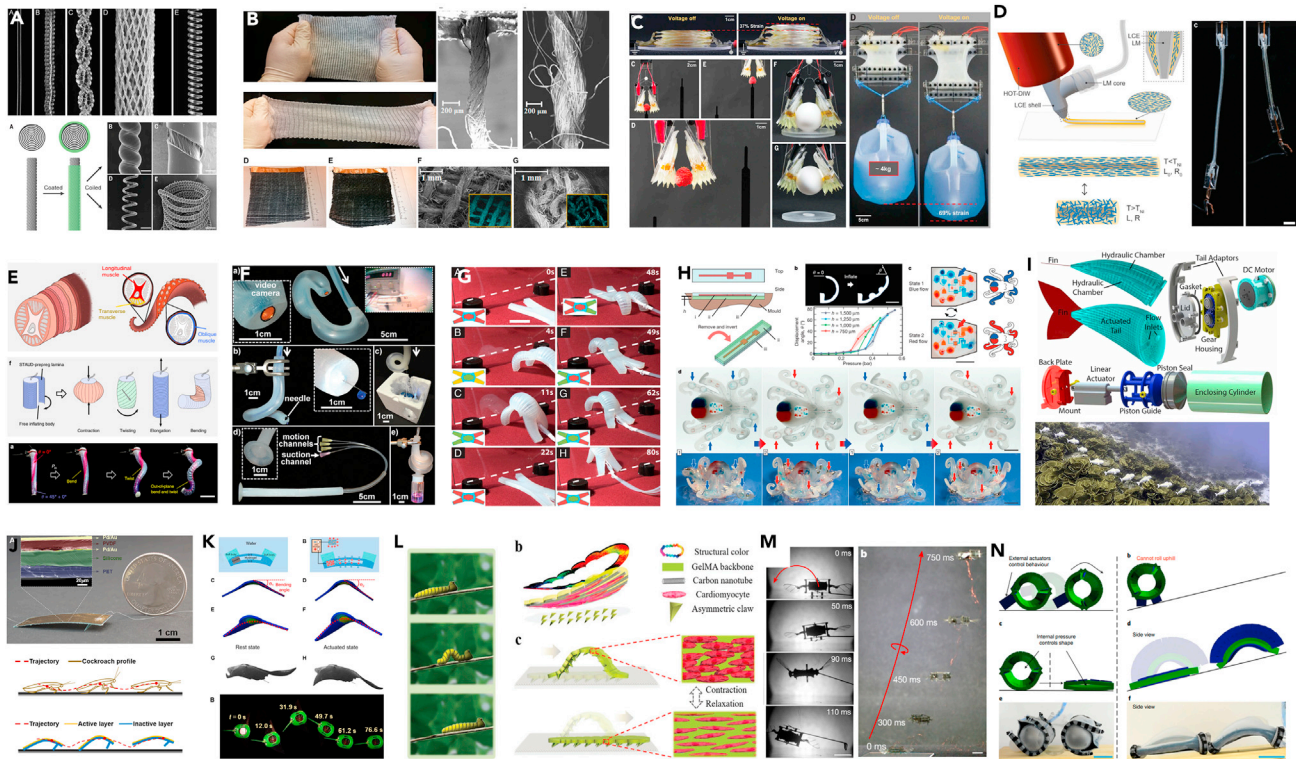
Soft actuation inspired by animal actuation

Most artificial muscles are currently limited to functional imitation owing to the complex hierarchical struc-tures and excitation mechanisms of biological muscles. However, functions possessed by biological mus-cles provide the functions that artificial muscles should possess. The development of artificial muscles currently focuses on the search for materials and mechanisms displaying muscle-like characteristics at the macrolevel. The essential characteristics such as nonlinearity, time variable, repeatable performance, and exquisite level of control of muscles render their imitation in engineering more challenging.

On the other hand, artificial muscles use the properties of materials as the basis for deformation instead of mimicking natural macroscopic strains formed by combined effects of trillions of molecular actuators. Similar to biological muscles, artificial muscles actively contract and/or actively expand in length when excited by a stimulus such as electric/magnetic field, thermal energy, electrochemical energy, fluid pres-sure, and light (Mirvakili and Hunter, 2018; Zhang et al., 2019a, 2019b, 2019c). As reported by Baughman et al., polyethylene and nylon fibers used in fishing lines and sewing thread could easily be transformed by twist insertion to provide fast, scalable, nonhysteretic, long-life tensile, and torsional muscles. The high orientation of these materials along their lengths would induce anisotropic thermal expansion with contraction in the length of around 49% and lift loads over 100-fold heavier than human muscles of the same length and weight (Haines et al., 2014). Later on, the same authors reported a novel struc-ture—sheath-run artificial muscles by infiltrating volume-changing yarn guest within yarn-like hybrid yarn artificial muscles (Mu et al., 2019). Such change increased the maximum work capacity by 1.70- to 2.15-fold for tensile muscles. The resulting sheath-run electrochemical muscle generated 1.98 watts per gram of average contractile power (Figure 6A). Jager et al. reported textile actuators produced from cellulose yarns assembled into fabrics and coated with conducting polymers. The scale-up by the parallel assembly of single fibers amplified the strain according to stretchable patterns, leading to better mechanical stability (Figure 6B) (Maziz et al., 2017). Keplinger et al. fabricated one of the best performing artificial muscles so far, consisting of hydraulically amplified self-healing electrostatic (HASEL) muscle (Figure 6C) (Acome et al., 2018). They fabricated a stack of five donut HASEL actuators with 37% linear strain harnessing electrostatic and hydraulic forces accompanied with inherent self-healing. On the other hand, except for yarns and hy-draulic forces, most smart materials can spontaneously contract and expand under stimuli from the external environment. These include liquid crystal elastomers (LCEs) (Ford et al., 2019; Kotikian et al., 2021), shape memory alloys (Hartl et al., 2010; Huang et al., 2019), dielectric elastomers (DEs) (Brochu and Pei, 2012; Peng et al., 2021), conducting polymers (Ismail et al., 2020; Li et al., 2011), stimuli-responsive gels (Xia et al., 2013), piezoelectric actuators (Xu et al., 2010), electrostrictive actuators (Liu et al., 2018), magneto-strictive actuators (Villegas et al., 2012), and photostrictive actuators (Takagi et al., 2004). Hence, these materials are a promising alternative to traditional artificial muscle materials. For example, this extru-sion-based direct ink writing method enables coaxial filamentary features composed of pure liquid metal core surrounded by an LCE shell showed programmed, self-sensing 3D shape change with closed-loop control (Figure 6D) (Kotikian et al., 2021).

The hydrostatic skeleton consists of a fluid-filled cavity surrounded by a tissue-fiber-reinforced muscle wall. Two muscle fiber orientations may antagonize each other, generating various movements (Kier, 2012). Inspired by the fiber architecture of the muscular hydrostat, Kramer-Bottiglio et al. developed a self-adhe-sive composite lamina made of a hyperelastic matrix with unidirectionally embedded inextensible fibers (Kim et al., 2019a, 2019b). The resulting muscle was extremely stretchable in the direction perpendicular to the fibers and inextensible along the fibers (Figure 6E). In many fluid-driven actuators, preprogrammed channels are used to generate movement in three dimensions. Whitesides et al. fabricated soft tentacles with three indistinguishable channels along the longitudinal direction of the tentacle for enabling both bending and twisting movements (Figure 6F) (Martinez et al., 2013). More optimized designs have been proposed in recent studies to achieve faster response, more complex deformation, and better mechanical performance. Moreover, artificial hydrostatic skeleton might systematically be designed to achieve more

Figure 6. Soft actuators inspired by the animal actuation system

(A) Artificial muscles made of twist insertion of fishing line and sewing thread. Adapted with permission from Haines et al., 2014. Copyright 2014, American Association for the Advancement of Science (AAAS).

(B) Artificial muscles made of knitted stretchable fabric with specific textile construction. Adapted with permission from Maziz et al., 2017. Copyright 2017, AAAS.

(C) Artificial muscles enabled by hydraulically amplified self-healing electrostatic. Adapted with permission from Acome et al., 2018. Copyright 2018, AAAS.

(D) Artificial muscles composed of liquid crystal elastomers embedded with liquid metal microparticles. Adapted with permission from Kotikian et al., 2021. Copyright 2021, John Wiley and Sons.

(E) Artificial hydrostatic skeleton enabled by self-adhesive composite lamina composed of a hyperelastic matrix with unidirectionally embedded inextensible fibers. Adapted with permission from Kim et al., 2019a, 2019b. Copyright 2019, Springer Nature.

(F) Artificial soft robotics composed of three indistinguishable channels along the longitudinal direction of the tentacle. Adapted with permission from Martinez et al., 2013. Copyright 2013, John Wiley and Sons.

(G) Artificial soft robotics composed of chambers embedded in a layer of extensible elastomer and bonded to an inextensible layer. Adapted with permission from Shepherd et al., 2011. Copyright 2011, NAS.

(H) Artificial soft robotics composed of pneumatic actuator networks, on-board fuel reservoirs, and catalytic reaction chambers. Adapted with permission from Wehner et al., 2016. Copyright 2016, Springer Nature.

(I) Artificial soft robotics composed of a closed-circuit drive system that uses water as a transmission fluid. Adapted with permission from Katzschmann et al., 2016. Copyright 2016, Springer Tracts in Advanced Robotics.

(J) Terrestrial locomotion of insect-scale fast-moving and ultrarobust soft robot. Adapted with permission from Wu et al., 2019. Copyright 2019, The American Association for the Advancement of Science.

(K) Aquatic locomotion of electronic fish with a fully integrated onboard system for power and remote control. Adapted with permission from Li et al., 2017. Copyright 2017, The AAAS.

(L) Subterranean locomotion of the cardiomyocytes-driven soft robot with the capacity of running along the tracks. Adapted with permission from Sun et al., 2020. Copyright 2020, John Wiley and Sons.

(M) Aerial locomotion of aerial robots with open-loop control, passively stable ascending flight as well as closed-loop, hovering flight. Adapted with permission from Chen et al., 2019. Copyright 2019, Springer Nature.

(N) Shape-changing robots with shape- and mechanical-properties-changing ability in real time according to external feedbacks. Adapted with permission from Shah et al., 2021b. Copyright 2021, Springer Nature.

complex biological-like behaviors such as creeping, swimming, climbing, and jumping similar natural hydrostatic skeletal systems such as squid, starfish, and worms. As shown in Figure 6G, Whitesides et al. proposed a multigate soft robot with combed crawling and undulation gaits, allowing it to navigate difficult obstacles (Shepherd et al., 2011). Then, they fabricated a more integrated soft and untethered robot

controlled by microfluidic logic and fueled by monopropellant decomposition (Figure 6H) (Wehner et al., 2016). Rus et al. developed an autonomous soft-bodied robotic fish hydraulically actuated by its soft tail made of two fluidic chambers (Figure 6I) (Katzschmann et al., 2016).

The locomotion mechanisms of animals also inspired several designs of soft robots. Some deformation behaviors of soft actuators do not result from biological structures such as muscles and hydrostatic systems, but rather biological motion modalities such as terrestrial, aquatic, subterranean, aerial motions, and manipulation. Inspired by arthropods with rapid and cyclic locomotion at high frequencies, Lin et al. developed an insect-scale fast-moving and ultrarobust soft robot with curved unimorph piezoelectric structure (Figure 6J) (Wu et al., 2019). The fabricated prototype reached a relative speed of 20 BL/s under an alternating current of 850 Hz. Moreover, the robot remained robust and moved afterward even under 59.5-kg pressure load. Based on the structure and propulsion mechanism of flapping pectoral fins, Li et al. designed an electronic fish with dielectric elastomers membranes as the muscle and silicone as the body equipped with a fully integrated onboard system for power and remote control (Figure 6K) (Li et al., 2017). The resulting electronic fish could swim at a speed of 6.4 cm/s (0.69 body length per second). Inspired by the crawling mechanism of snakes and caterpillars in nature, Zhao et al. made a cardiomyocytes-driven soft robot composed of claws-like snakeskin, a parallel carbon-nanotube-assisted myocardial tissue layer, and a structural color-indicator layer (Figure 6L) (Sun et al., 2020). The resulting robot can run along the track at different speeds depending on the stimuli level in the track. Flying mosquitoes swing their wings at the frequency of about 800 Hz and 1-mm-long mites moving at 200 body lengths per second have also been reported. Wood et al. developed aerial robots powered by multilayered dielectric elastomer actuators with open-loop control, passively stable ascending flight, closed-loop control, and hovering flight (Figure 6M) (Chen et al., 2019). Most recently, many literature studies related to robots that change shape to enhance and expand their functionality mimicking locomotion of animals are presented (Shah et al., 2021a, 2021b). Shah et al. reported shape-changing robots which could change their shape and mechanical properties in real time according to the external feedback received to switch gaits and adapt to different environments (Figure 6N) (Shah et al., 2021b).

Mechanoreception in the biological world

As proposed by Robert Louis Stevenson, life is a permanent possibility of sensation (Virginibus, 1903). Tactile sensing provides key information related to changes in the surrounding environment, including the location and surface properties of objects. Through long-term optimization, natural organisms have evolved effective structures and functions to transduce incoming physical information into biosignals. Living organisms depend on real-time and stored information to react. These functions are provided by specialized receptors comprising animal somatosensory systems or the chemical molecular signaling for the plant sensory system.

For robots, somesthetic sensation and proprioception are essential types of sensing components. In animal systems, somesthetic sensation arises from the integument, as well as some internal organs such as touch, pressure, temperature, pain, and electrical fields. In addition, proprioception arises from muscles, tendons, and joints to provide information on limb position and motion. Animals such as chameleons and octopus are capable of coloration resulted from structural changes in cells for attraction, warning, and disguise (Nie et al., 2021), which already has many related reviews and will not be discussed here. Here, the structures and functions of tactile sensing in the biological system are summarized in the following two subsections.

Structural motifs of mechanotransduction in the biological world

Animals and plants have evolved efficient strategies to enhance somesthetic sensation and proprioception performance. Their prototype and functions are provided in Figure 7. Various structures, namely fingerprint, interlocked, porous, whiskers, hierarchical, and crack structures, have been discovered in natural organisms. These structures play important roles in accomplishing sensory tasks, including precise and ultrasensitive detection of subtle signals, high sensitivity over wide detection ranges, fast response time, and linear response (Amoli et al., 2019). The average adult human skin measures a total area of about 2 m^2 (Gallo, 2017). The human skin could sense forces as low as 10 Pa with a response time of $\approx$ 15 ms (Chortos et al., 2016). Therefore, many structures originating from human skin possess superior sensory performances. One of the typical structures in the human skin is fingerprint structure, which is essential for interacting with the physical environment for precision manipulation of objects and discrimination of textures (Figure 7A). Fingerprints contribute to enhanced friction force, enabling precise and steady grasping of
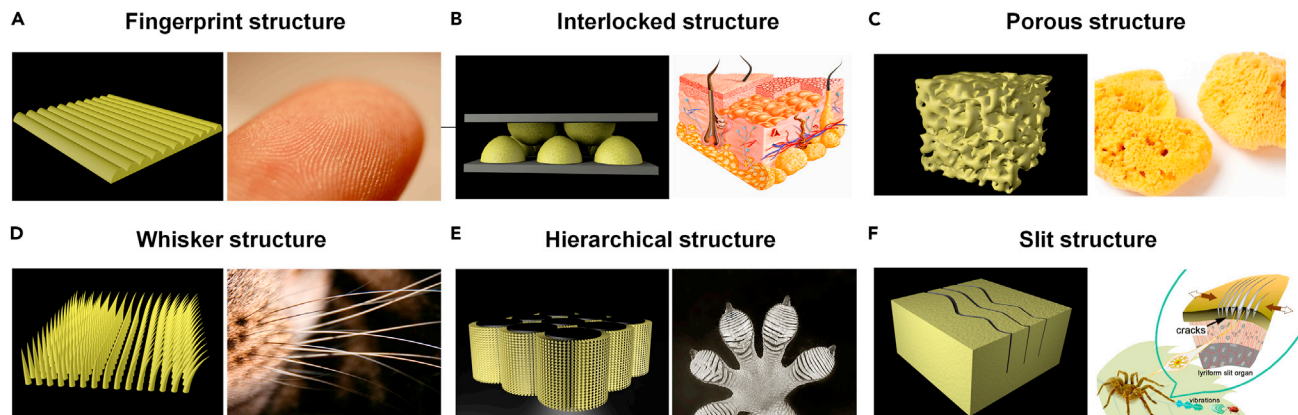
Figure 7. Overview of mechanotransduction structural and functional motifs (left) and prototypes (right) in the natural world
(A–F) (A) fingerprint structure, (B) interlocked structure, (C) porous structure, (D) whisker structure, (E) hierarchical structure, (F) slit structure.

objects. In tactile perception, the structure of fingerprints could also amplify subsurface strains by enabling the spectral filtering properties of the skin in dynamic tactile exploration, thereby endowing humans with the tactile perception of extremely fine textures (spatial scale <200 micrometers) (Zhao et al., 2021). The top layer of the dermis skin in humans has a unique structure consisting of interlocked epidermal-dermal junction (Figure 7B) (Boutry et al., 2018; Park et al., 2015). The variations in the structure and elastic modulus of those microdomes provide human skin with highly sensitive and multidirectional sensation. The dome-shaped structure generates stress concentration at the contact points for enhancing the sensitivity. Besides, the interlocked arrays can discriminate the stimuli from all directions to yield multidirectional sensitive sensors.

Porous structures existing in spongia officinalis, diatoms, and mushrooms also contribute to high sensitivity through effective deformation of the sensing matrix under slight pressure or strain vibration (Figure 7C). For instance, spongia officinalis possesses complex hierarchical pore structures suitable for deformation under subtle pressure (Kang et al., 2016). In turn, the hierarchy and porosity endow the matrix material with high sensitivity and low density.

Hierarchical structures are widely observed in the biological world and serve diverse functions (Figure 7D). For instance, the gecko's feet have hierarchical microstructures/nanostructures to create adhesion to any surface (Sitti and Fearing, 2003). Besides, the hierarchical structure of flower surface, pollen, and stumps can be used as a biomass template to confer high porosity, flexibility, and low-density sensors (Wang et al., 2018a). On the other hand, although these hierarchical structures in nature might not possess enhanced sensitivities, they can endow tactile sensors with high sensitivity, fast response, and durability.

Whiskers are coarse, long, widely spaced hairs found in mammals such as cats, rats, and seals. Each whisker is connected to several sensory dendrites that convert stimuli into bioelectrical signals using lever amplification roles (Figure 7E) (Sofroniew et al., 2015). Therefore, those creatures can feel the subtle changes such as air currents, changes in air pressure, temperature, or wind direction. For example, the whiskers of cats can detect the location of the moving objects even in the dark. In order to capture animals, they move their whiskers back and forth to gather information about their prey.

Spiders are the most vibration-sensitive creatures on earth. They can detect the movements of objects and airflow to locate prey and sense potential danger thanks to their series of slits called "lyriform organ." The reason for this has to do with the variation in slit length similar to the strings of a lyre (Figure 7F) (Barth and Stagl, 1976). The functioning mechanism of such sensors consists of vibrations able of opening and closing cracks, thereby acting as an incredible amplification in reaching extremely high sensitivity (Kang et al., 2014).

Flexible mechanosensors inspired by structural sensory motifs

The common sensing mechanism in flexible tactile sensors relies on the electrical signal produced by geometry deformation of the material under external mechanical forces. However, devices based on

traditional designs are insufficient for soft robotics owing to the poor sensitivity, sensing range, response time, and limit of detection. Moreover, multifunctionality linked to the ability to sense simultaneously various forces, such as normal, shear, and tensile forces, coupled to multidirectionality or the ability to discriminate multidirectional forces such as normal, shear, or torsion forces and tactile sensing features is highly desired.

Therefore, significant biomimetic flexible sensors have been fabricated in an attempt to solve these tricky issues. Based on the extraordinary sensing ability of fingerprint for the perception of subtle textures, many research studies have been conducted to amplify tactile information (Chen et al., 2018a; Chortos et al., 2016; Park et al., 2015). Zhang et al. reported a spiral-shaped fingerprint-inspired triboelectric sensor capable of detecting both the sliding direction and speed without external power (Figure 8A, top) (Chen et al., 2018a). For piezoelectric e-skins, fingerprint structures could facilitate the perception of surface textures. Ko et al. used parallel ridges to amplify texture-induced vibrations and detect different surface roughness (Figure 8A, bottom) (Park et al., 2015). Geometrical parameters such as shape, size, and space of microstructure arrays were controlled to enhance the mechanical sensitivity and operation range of the sensors. Inspired by the stiff epidermis and soft dermis layers, Ko et al. developed triboelectric e-skins based on interlocked geometry with good gradient stiffness (Figure 8B, top) (Ha et al., 2018). The resulting skins were able to differentiate multidirectional tactile stimuli, resulting in highly sensitive sensors capable of detecting human vital signs and voice. Cheng et al. fabricated a flexible pressure sensor with an irregular pattern mimicking the mimosa leaf with the regime of 0–70 Pa and sensitivity of 50.17 kPa^{-1} (Figure 8B, bottom) (Su et al., 2015). In nature, living organisms such as *Spongia officinalis* could be effectively deformed even by subtle pressure owing to their porous structures. For example, the porous structure of Spongia officinalis is responsible for its high sensitivity, soft bendability, and reversible compressibility. Lee et al. fabricated sponge-like porous polydimethylsiloxane (PDMS) for piezocapacitive tactile sensors based on sponge-like structure of PDMS thin-film dielectric layer (Figure 8C, top) (Kang et al., 2016). The obtained porous structured pressure sensor exhibited high sensitivity, good stability, and fast response time. Park et al. reported a flexible piezoelectric sensor based on microporous dielectric elastomer with superior sensitivity and stable pressure sensing ability (Figure 8C, bottom) (Kwon et al., 2016).

Rodents use their whiskers to perceive spatial properties related to their surroundings. Whiskers amplify the stimuli from the environment and thereby can be used for fluid flow mapping, material stiffness inspection, tactile surface mapping, and friction measurements. Reeder et al. reported shape memory whiskers capable of translating external information (proximity, surface, friction, force, and material stiffness) into precise electrical signals (Figure 8D) (Reeder et al., 2018). Inspired by the hierarchical structures found in insect legs, gecko feet, and beetle wings, numerous microstructures have been fabricated to sense directional forces. Hierarchical structures inspired by gecko foot hairs have recently been introduced in tactile sensors to achieve high sensitivity, fast response, and good durability. For example, piezoresistive tactile sensors based on interlocked and hierarchical micropillars coated with nanowires demonstrated high sensitivity and ultrafast response (Figure 8E) (Ha, et al., 2015). Notably, the hierarchical structure increased the surface area, thereby amplifying the compression resistance, as well as providing high sensitivity and fast response. The presence of subtle slits in the legs allows the spider to detect small changes in airflow for locating prey. Inspired by the slit organs of insects, ultra-high-sensitivity slit sensors have been introduced for the precise detection of pressure and strain vibrations. Based on the crack-shaped slit organs of spiders, Kim et al. developed a multifunctional ultrasensitive sensor made of nanoscale crack junctions (Figure 8F) (Kang et al., 2014). The disconnection-reconnection of the crack junctions under vibration yielded a crack sensor with ultrahigh sensitivity to small vibrations.

Functional motifs of mechanotransduction in the biological world

The generation, transmission, and processing of electrical signals in animal tactile sensory systems are also good blueprint for future soft robotic (Amoli et al., 2019). The basic mechanotransduction process occurs by amplifying the mechanical stimulus through the aforementioned structures followed by a reception by mechanoreceptors (generation). During this process, the activated ion channels will convert the stimulus into an electrical signal by altering the membrane potential (transmission). Subsequently, the electrical signals transmit through afferent nerves to finally reach the brain or spinal cord for signal processing.

Mechanoreceptors in the human skin receive external stimuli as an initial sensory step of mechanotransduction (Figure 9A). The external mechanical stimuli trigger the transport of ions and generate electric signals
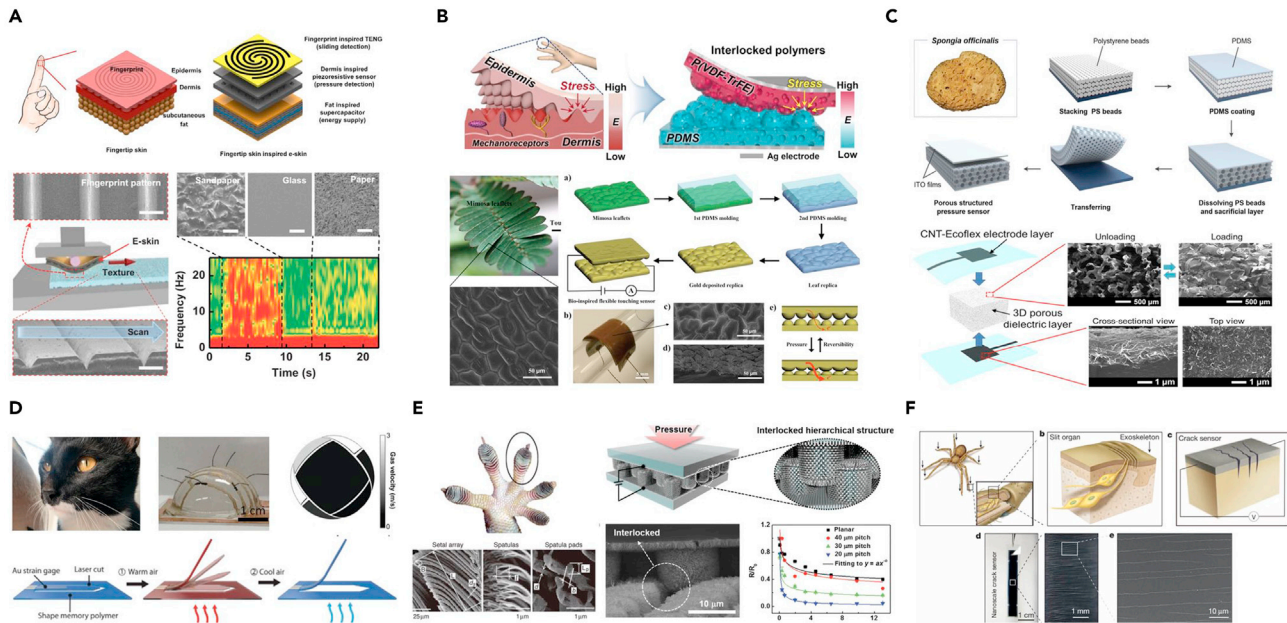
Figure 8. Flexible mechanosensors inspired by biological sensory motifs

(A) Spiral-shaped fingerprint inspired sensor for the detection of both sliding direction and speed (top), as well as the perception of surface textures (bottom). Adapted with permission from Park et al., 2015. Copyright 2015, AAAS; Adapted with permission from Chen et al., 2018a. Copyright 2018, Elsevier.

(B) Triboelectric e-skins based on the interlocked geometry with gradient stiffness differentiating multidirectional tactile stimuli (top) and flexible pressure sensors with an irregular pattern of microdomains sensitive enough to mimic mimosa leaves (bottom). Adapted with permission from Ha et al., 2018. Copyright 2018, American Chemical Society; Adapted with permission from Su et al., 2015. Copyright 2015, John Wiley and Sons.

(C) Piezocapacitive tactile sensors based on a sponge-like structure of dielectric layer (top) with high sensitivity, good stability, and fast response time along with flexible and wearable piezocapacitive pressure sensor based on a three-dimensional microporous Ecoflex dielectric elastomer with highly sensitive and stable pressure sensing (bottom). Adapted with permission from Kang et al., 2016. Copyright 2016, John Wiley and Sons; Adapted with permission from Kwon et al., 2016. Copyright 2016, The American Chemical Society.

(D) Adaptive electronic whiskers based on shape memory polymers able to translate proximity, surface topology, friction, force, material stiffness, and temperature into precise electrical quantities. Adapted with permission from Reeder et al., 2018. Copyright 2018, John Wiley and Sons.

(E) Piezoresistive tactile sensors based on hierarchical microstructures and nanostructures of micropillars with high-pressure sensitivity and ultrafast response time with minimal hysteresis. Adapted with permission from Ha, et al., 2015. Copyright 2015, John Wiley and Sons.

(F) Multifunctional ultrasensitive sensor mimicking nanoscale crack junction able of detecting subtle strains and vibrations. Adapted with permission from Kang et al., 2014. Copyright 2014, Springer Nature.

on the cell membrane of the mechanoreceptors. Based on the response to different mechanical forces, mechanoreceptors can be divided into slow adapting (SA) types (Merkel cells and Ruffini endings) and fast adapting (FA) types (Meissner's corpuscles and Pacinian corpuscles). The SA types respond to static forces, while FA receptors respond to dynamic forces (Purves et al., 2001). Besides, the distribution of the receptors achieves coordinated integration and optimized performance. For the distribution of the sensors in animal systems, somesthetic sensation (touch, pressure, temperature, pain, and electrical fields) arises from the integument and some internal organs. By comparison, proprioception arises from muscles, tendons, and joints to provide information on limb position and motion (Delhaye et al., 2018).

After activation of mechanoreceptors by various external stimuli (such as touch, pressure, stretching, sound waves, and motion), ion channels transmit the electrical signals from mechanoreceptors to the brains or spinal cord (Figure 9B) (Ranade et al., 2015). Note that ion channels are specialized proteins providing passageways for charged ions crossing the plasma membrane down to their electrochemical gradient. The channel response to specific stimuli is considered as a simple gating method.

In sensory neuronal systems, the application of mechanical stimuli to human skin incites the mechanoreceptors first to generate electrical signals via ion channels followed by propagation along the axon (Figure 9C) (LLOYD and CHANG, 1948). At the axon terminal, the changes in polarity caused by the action potential trigger the fusion of synaptic vesicles filled with neurotransmitters, thereby delivering the action
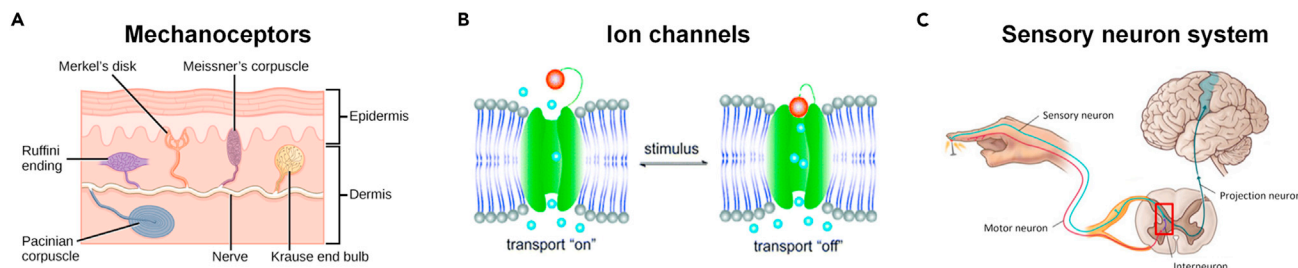
Figure 9. Overview of mechanotransduction functional motifs (left) and prototypes (right) in the natural world
(A–C) (A) mechanoreceptors, (B) ion channels, and (C) sensory nervous system.

potential from the presynaptic neurons to postsynaptic neurons. The induced signals are then sent along afferent axons to synapses of postsynaptic neurons for further processing in the central nervous system.

Flexible mechanosensors inspired by functional sensory motifs

Various types of rapid and slow adapting mechanoreceptors have been used in flexible sensors. Because piezoelectric and triboelectric electronic skins could instantaneously generate electrical signals, dynamic forces can be detected at high frequencies. By comparison, piezoresistive and capacitive sensors exhibit continuous sensing signals under sustained static forces, allowing the detection of low-frequency forces (Figure 10A) (Chun et al., 2018; Jin et al., 2017). Han et al. also emulated artificial ion-channel systems (Figure 10B) (Han et al., 2017), in which pressure sensors contained top and bottom reservoirs of polyaniline electrolytes separated by a nanopore membrane. Upon the application of stimuli, ions flowed through the membrane to generate piezoresistive current signals, enabling high sensitivity and operational stability of the sensor. Bao et al. obtained an artificial sensory neuronal system capable of converting time-dependent tactile signals into frequency-dependent signals (Figure 10C) (Kim et al., 2018). This system consisted of organic digital mechanoreceptors composed of the piezoresistive pressure sensor and an organic ring oscillator connected to an artificial afferent nerve to motor nerves, mimicking bio-electronic reflex arc.

DEVELOPMENT TRENDS OF BIOINSPIRED SOFT ROBOTICS: TOWARD CLOSED-LOOP CONTROL AND EMBODIMENT

Recent developments in soft robotics are centered on actuation capabilities. The intrinsic passive adaptability of soft materials endows soft robotics with normal functionality in the specific operational environment. No need of perception of their bodies and environments, they adapt only through the passive leverage of morphological and material properties (Gu et al., 2018; Usevitch et al., 2020; Verma et al., 2018; Wehner et al., 2016). However, achieving brain-like intelligence requires the brain (or controller) to quickly switch to different kinds of exploitation schemes either neutrally or mechanically through morphological variation. In other words, soft robots in the real world should cope with uncertain situations and react actively and quickly to changes in the environment. Working out the mechanism of biological systems and transferring them to soft robot design are effective solutions for creating soft robotics capable of operating in the real world. Intelligence requires a body, and biological lives rely on clever morphology associated with the shape of the body and limbs, as well as the type and placement of sensors and effectors (Pfeifer et al., 2007). Reasonable distribution of controlling and processing elements such as the central nervous system, material properties, sensor morphology, and interaction with the environment would tackle challenges faced by soft robotics. Thus, how embodiment enabled the evolution of soft robotics from open-loop control to closed-loop control will be introduced in the next four subsections.

Open-loop control

Open-loop controllers have commonly been used in high-speed trajectory-tracking tasks with minimum control effort. For instance, the universal robotic gripper proposed by Jaeger et al. could conform itself to a target object and hold it without requiring sensory feedback (Figure 11A) (Brown et al., 2010). In the system, the hand can automatically adapt to the object such as a human hand without knowing the shape of the to-be-grasped object. Without sensing and control modules, the morphology and materials can function as computational modules, so-called "morphological computation."
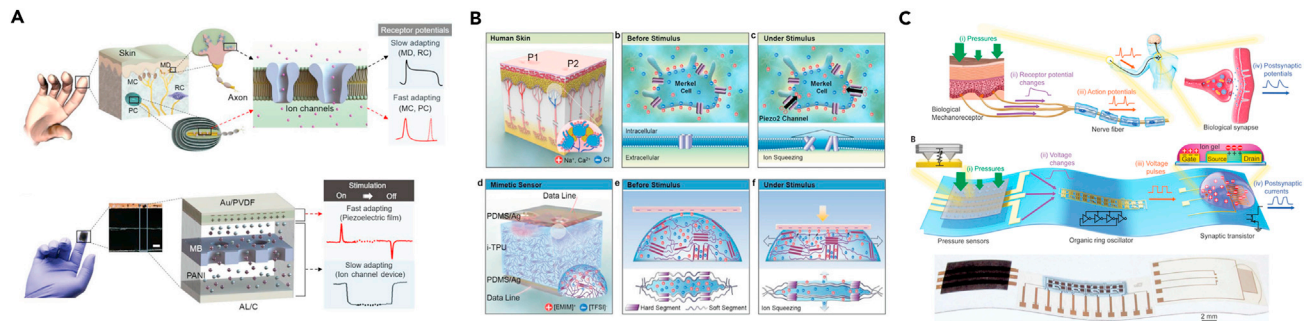
Figure 10. Flexible mechanosensors inspired by biological sensory motifs

(A) Piezoresistive and capacitive e-skins based on mechanoreceptors capable of sensing low-frequency forces. Adapted with permission from Chun et al., 2018. Copyright 2018, John Wiley and Sons; Adapted with permission from Jin et al., 2017. Copyright 2017, John Wiley and Sons.

(B) Pressure sensors mimicking artificial ion-channel systems with ultrahigh sensitivity and operational stability over a wide range of mechanical stimuli. Adapted with permission from Han et al., 2017. Copyright 2017, The Royal Society of Chemistry;

(C) Artificial sensory neuron system capable of converting time-dependent tactile signals into frequency-dependent signals. Adapted with permission from Kim et al., 2018. Copyright 2018, The American Association for the Advancement of Science.

While in most cases, such as fully integrated soft octobot (Wehner et al., 2016), locomotion robot (Ji et al., 2019) and manipulation robot (Renda et al., 2014) are required to possess sensing capabilities to enhance the efficiency and reliability, as well as achieve surface texture discrimination and dexterous manipulation and prevent mechanical failure.

Closed-loop control based on responsive material

The functionality of soft robotics is closely related to material morphology. The design of robots depends on the task at hand and can be achieved by altering their shapes. The term "morphofunctional machines" is used to designate soft robotics that can change their functionalities not only by the change in control but by modification of morphology. However, the tasks performed by the controller in the classical robotic approach can now be partially taken by materials intelligence.

Material intelligence is an emerging research paradigm integrating responsive materials and mechanical design principles as independent machines (McCracken et al., 2020). Similar to sensor-diagnosis-actuation systems in Venus flytrap and other stimulus-responsive plants, intelligent robots sense the stimuli from the environment and transduce the free energy, such as heat, light, and magnetic field into forces and motions. However, this mechanism is mostly unidirectional. By comparison, response materials sense external stimuli and output the forces and motions through embodied computation (Figure 11B). For example, Priimagi et al. developed a light-driven artificial flytrap with autonomous closure and object recognition competence without incorporating complex computing circuitry and power sources (Wani et al., 2017). Hu et al. designed a light-driven autonomous bistable actuator based on carbon nanotubes, resulting in autonomous response to external stimuli (Yang et al., 2020). This robot generated continuous self-oscillating motion and enabled self-sensing ability. Stimuli-responsive materials, such as humidity-responsive materials (Cheng et al., 2019; Han et al., 2018; Kotikian et al., 2019), light-responsive materials (Shahsavan et al., 2020; Wang et al., 2019), thermal responsive materials (Zhang et al., 2019a, 2019b, 2019c; Zolfaghar-ian et al., 2016), and magnetic-responsive material (Kim et al., 2019a, 2019b; Schmauch et al., 2017), have been broadly applied in soft robotics through the incorporation of morphology computation. Such actuations are considered as physical processes but still computationally relevant for neural processing. More recently, researchers have begun to develop shape changing robots, which are capable of editing their own structure to more efficiently perform tasks under changing demands. However, most of them are manually manipulated to actively change their shape to adapt to their environment or gain new functionalities, and their dynamic control is highly demanded for next-generation shape-changing robots (Shah et al., 2021a, 2021b).

In addition to spontaneous actuation, some smart materials also present self-awareness and external perception. These materials could output external signals by the changes in their physical/chemical properties resistance, capacitance, such as ferrastase, magnetic intensity, and light intensity. For example, soft actuators made with shape memory alloys, conductive nanomaterials (Chen et al., 2020; Wang et al.,
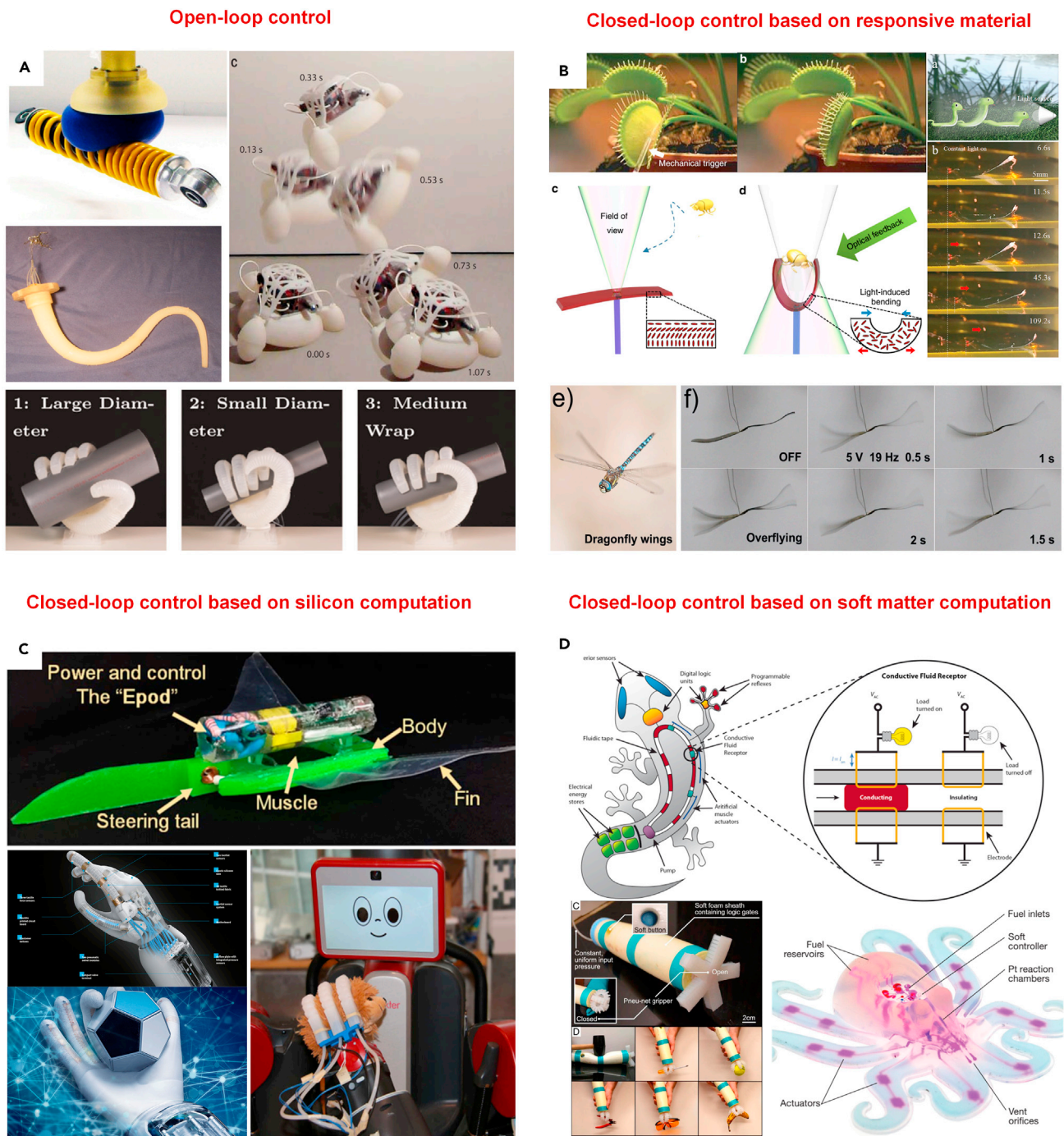
Figure 11. Four integration trends of soft robotics

(A) Open-loop system based on the morphological computation of soft materials for self-adaption. Adapted with permission from Brown et al., 2010. Copyright (2010), The National Academy of Sciences.

(B–D) (B) Closed-loop system based on material intelligence of responsive material for embodied computation. Adapted with permission from Wani et al., 2017. Copyright (2017), Springer Nature (C) Closed-loop system based on the computation of silicon-based elements for on-board and off-board control. Adapted with permission from Li et al., 2017. Copyright (2017), The American Association for the Advancement of Science (D) Closed-loop system based on the computation of soft matter for embodied control. Adapted with permission from Preston et al., 2019. Copyright (2019), The National Academy of Sciences.

2018b), conductive ion gels (Truby et al., 2018), liquid metals (Oh et al., 2020; Spina et al., 2019), dielectric elastomers (Hoffstadt and Maas, 2019; Xu et al., 2015), and ionic polymer-metal composites (Kruusamäe et al., 2010; Punning et al., 2007) could self-sense by detecting changes in resistance/capacitance.

Closed-loop control based on silicon computation

Soft robots in the real world require highly sophisticated computation systems because they are often confronted with processing large amounts of information in real time. The closed-loop control relies on the engineering of stimuli-response relationships/morphological computation, capable of producing comparatively simple actuation modules primarily focused on component-level demonstrations of subsystems such as a hand or gripper. Just like a biological organism, constructing higher level behaviors such as decision-making, adaptation, and learning requires integrated multimodal sensors into soft-bodied systems to provide proprioception and exteroception sensory feedback. Thus, textile-based sensors (Farrow and Correll, 2015), ionic-liquid-based sensors (Russo et al., 2015), liquid-metal-based sensors (Morrow et al., 2016), nanocomposite-based sensors (Rocha et al., 2018; Tavakoli et al., 2017), and optical fiber sensors (Wang et al., 2016; Zhuang et al., 2018) have been attached/embodied in soft robots and prosthetic hands to sense and adapt to the environment.

Although integrating sensors and actuators into robots are commonly seen, fully autonomous prototypes demand not only the acquisition of sensor signals but also local and global data processing. Here, algorithms related to the artificial neural network were not discussed owing to massive reviews existed in this field. Here, we discuss the hardware of the control systems instead.

Feedback control based on excitatory controllers is commonly used in traditional robotics. These components tether external rigid silicon-based computing elements, such as electronic microcontrollers into soft systems (Figure 11C). The integration of rigid components into soft and flexible substrates has attracted increasing attentions. Silicon-based microcontrollers do not bond well to soft materials but often tether with soft bodies of robots (on-board) or as an external processing end (off-board). For instance, the fast-moving robot fish proposed by Li et al. used an integrated on-board eight-pin microcontroller to tune the voltage frequency and amplitude with infrared (IR) remote control (Li et al., 2017). It is worth noting that off-board computing systems are more common than on-board systems. The Festo corporate developed a bionic soft hand using reinforcement learning and embedded tactile sensors to precisely control the robot fingers. Besides, Katzschmann et al. proposed a soft hand capable of robustly grasping and identifying objects based on resistive forces, curvature sensors, and an off-board controller (Homberg et al., 2019).

Closed-loop control based on soft matter computation

In addition to the aforementioned routes, another feedback control based on the inhibitory controller of soft computing has also been used. This method is promising for future soft robotics owing to its compatibility with printing methods and enabling large-area coverage at a low cost. Integrating soft computational mechanisms into soft robotics would allow soft robots to retain all of the benefits of soft materials and moving toward the intelligent and adaptive materials of natural systems.

The first soft computation strategy is based on organic and flexible neuromorphic devices. The human brain performs efficient information processing, learning, and memory tasks with extremely low energy consumption. As a result, brain-inspired computing has emerged as a new computing paradigm for enabling massive parallel analog computing (Tang et al., 2019; Wan et al., 2020). For example, organic-based flexible neuromorphic devices have been used to imitate the nervous system of human brains (Tuchman et al., 2020; Zhu et al., 2019). The initial efforts related to ionic floating gates, perceptron-based artificial neural networks, and electro-polymerization have been built to realize organic-based neural networks (Park et al., 2020). For instance, an organic artificial afferent nerve for the detection of moving objects was successfully developed (Kim et al., 2018). A sensory device with tactile learning consisting of organic optoelectronic synapses and stretchable organic nanowire synaptic transistors was also reported (Wan et al., 2018). The resulting synaptic outputs can be used for light-interactive actuation of an artificial muscle mimicking the contraction of a biological muscle fiber. Such organic-based flexible neuromorphic devices showed good biocompatibility, low-power consumption, and relevant flexibility. They also displayed low elastic moduli and compatibility with printing methods, enabling large area coverage and reliable bonding with soft robots (Park et al., 2020). Integration of artificial synapses with sensing/motor

elements enables emulation of sensing elements and responding behaviors of biological systems, which will be the core technology of soft robotics.

The second soft computation strategy is based on embedded soft matter computers (Figure 11D) (Preston et al., 2019; Rothemund et al., 2018; Wehner et al., 2016). Soft computation is inspired by the vascular system, in which information can be processed locally in different organs. Garrad et al. described a soft matter computer with a soft matter tube containing two electrodes parallel to the direction of fluid flow (Garrad et al., 2019). The injection of an insulating and conducting fluids pattern into the tube generated a binary control signal. The soft matter computers could be embedded within the robot body. Whitesides et al. described a soft pneumatic bistable valve relying on snap-through instability of the hemispherical membrane (Preston et al., 2019). These works represented a step toward embodied control functions into soft devices, enabling autonomy and "intelligent" behavior without requiring electronic interface or hard components.

However, both mentioned flexible computing strategies, especially embodied soft matter computers still suffer from issues related to miniaturization and computing capabilities. Complementarily, the morphological computation could ease the burden of centralized computation. This strategy is prevalent in biological systems, such as in cockroaches with strong motor abilities such as walking on uneven terrain and crossing obstacles. The leg movements of cockroaches possess only about 250 neurons and are controlled by altered joint morphology. Instead of manipulating movements, the brain manipulates locomotion through an ingenious kind of cooperation with the body and decentralized neural controllers. Consequently, only a few global parameters require altering to achieve the desired movement. This kind of control through morphological computation is promising for future soft robotics to free them from redundant control tasks (Pfeifer et al., 2007).

CHALLENGES AND PERSPECTIVES

Biology has so far offered tremendous inspiration for soft actuators and flexible sensors. Nevertheless, natural systems are highly organized entities that exploit intricate multiscale structures and multimodules to maintain their structural integrity (Egan et al., 2015). Obtaining highly integrated and autonomous bio-inspired soft robots as natural lives are still facing enormous challenges. Owing to the intrinsic soft feature, the mechanical coupling of actuators, sensors and controlling electronics, accurate deformation modeling, and advanced data processing algorithms are quite challenging for the development of integrated soft robotics (Yang et al., 2018).

First, the seamless integration of modules at high densities in a scalable fashion is still a major challenge (Wang et al., 2018b). The size of existing flexible sensors and computing units is difficult to miniaturize, and when many sensors and computing units are installed, manufacturing and control techniques will be tricky. Biological organisms are not "made" but "become," and thus a big gap between "man-made soft robotics" and "born natural lives" still exists (Broom and Broom, 1981; Pross, 2016). Innovations in robust and high-performance multimodal sensors and fully integrated electronic are highly demanded.

Another issue is to address deformation modeling of soft robotics. Conventional approaches to rigid robot control are a poor fit for controlling soft bodies. It is challenging in accurate modeling of the complex behavior and large deformation of these hyperelastic materials of soft robotics. Finite-element methods (FEMs) and other advanced techniques with high computational capacity are being developed to model mechanical sensing of deformations (Coevoet et al., 2017).

Lastly, soft materials require advanced data processing algorithms and computation modules. Organic and flexible neuromorphic devices provide the opportunity for enhancing the computational and cognitive power of robots (Seminara et al., 2019). On-board soft computation systems based on fluid materials and nanomaterials also propose new strategies for the construction of entirely soft robots (Garrad et al., 2019). The concept based on "shape-changing robots," "embodied intelligence," and "morphology computation" can also minimize sensing and computation pressures (McCracken et al., 2020; McEvoy and Correll, 2015; Shah et al., 2021a, 2021b). Besides, tools from data science, machine learning, artificial intelligence (AI), and 5G wireless technologies are crucial for advancing soft robots with remote and real-time control.

The human fascination with robots is far more than a specific cold-mechanized facility. Natural organisms remind a human wishful vision of the future advancement of soft robotics. Achieving robotic ubiquity not

requires the replication of natural lives but goes beyond them. Although this review is devoted to soft robotics, it is undeniable that some notable drawbacks such as low positioning accuracy, moderate forces, and complicated control still exist. Hybrid soft robotics with a combination of soft and hard materials will be the mainstream of future robots. Soft robotic research is accelerating around the globe. The flourishing of soft robotics will boost clinical, aerospace, military, wearable, and implantable fields, and exciting times of soft robotics are ahead waiting for exploration.

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AUTHOR CONTRIBUTIONS

Bingqian Li and Luquan Ren contributed equally to this work, and they drafted the manuscript under the supervision of Qingping Liu and Lei Ren. All the authors commented on and revised the manuscript.

DECLARARION OF INTERESTS

The authors declare no competing interests.

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