

Untethered soft robotics

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Research in soft matter engineering has introduced new approaches in robotics and wearable devices that can interface with the human body and adapt to unpredictable environments. However, many promising applications are limited by the dependence of soft systems on electrical or pneumatic tethers. Recent work in soft actuation and electronics has made removing such cords more feasible, heralding a variety of applications from autonomous field robotics to wireless biomedical devices. Here we review the development of functional untethered soft robotics. We focus on recent advances in soft robotic actuation, sensing and integration as they relate to untethered systems, and consider the key challenges the field faces in engineering systems that could have practical use in real-world conditions.

Recent work into soft robotics^{1–3} and flexible electronics⁴ has sought to improve the biocompatibility and versatility of conventional robots in unstructured environments. Often, these devices take inspiration from biology, mimicking the elasticity of skin to improve the impedance matching of human–machine interfaces, or imitating the softness and flexibility of organisms like the octopus to adapt to unstructured environments and thereby create novel robotic functionalities. An artist's conception of the latter, inspired by current state-of-the-art efforts in soft octopus robotics^{5,6}, is shown in Fig. 1a. Electric and dynamically responsive materials with compliance comparable to these biological systems are particularly important for human–machine interaction, wearable computing^{7,8}, health monitoring⁹ and physically assistive robotics^{10,11}, which provide intrinsic safety and comfort to the user.

For a soft system to be useful in wearable or field robotics, its essential components (for processing, actuation and power) must be fully integrated and embedded within its own structure. Thus far, attempts at integration have revealed significant trade-offs: fully soft systems often require a tethered connection to support pneumatic or electrical hardware, while untethered systems typically depend on bulky on-board components such as batteries, microprocessors, pumps or motors. Although fully soft and untethered robots with limited functionality have recently been demonstrated¹², there are a number of questions relating to actuation, sensing and subsystem integration methods that must be answered before untethered soft systems can become widely practical.

Soft actuation methods exploit a wide range of physical mechanisms to induce deformation in soft materials, including pneumatic inflation, combustion, phase transition, electrostatic force, electro-osmotic flow and biological actuation. No technique has yet emerged as the principal method of actuation, with performance trade-offs existing between force, speed, displacement, auxiliary equipment requirements and reliability. Work in the field continues to focus on improving the characteristics of these various soft actuators without sacrificing performance.

Developing these actuators into viable technologies has yielded novel methods of achieving functionality in soft systems, which can be divided into three main approaches: geometry-enabled (also known as 'deterministic') structures, fluid–elastomer composites and bio-hybrid systems (Fig. 1b). Deterministic structures achieve macroscale compliance through the selective patterning of rigid materials (for example, in meshed, coiled or truss-like architectures)

into shapes that are deformable in response to certain prescribed loading directions^{9,13,14} (Fig. 1bi,ii). Fluid–elastomer composites incorporate intrinsically soft materials (for example, elastomers, ionic fluids or liquid metals) to achieve compliance and elastic deformability in all loading directions (that is, isotropic compliance) at all length scales^{15,16} (Fig. 1biii,iv). Although these structures may require careful microscale engineering, they differ from deterministic structures because they achieve electronic functionality or actuation with fluids rather than traditional rigid materials. Finally, bio-hybrid systems incorporate biological tissue to achieve soft and biocompatible structures for actuation and sensing^{17–19} (Fig. 1bv,vi). Although potentially promising for use in the future, such bio-hybrid systems are not currently robust enough to handle conventional applications and environments. This is due to limitations in materials and structures, and the need to keep tissue alive.

Many recent developments have brought us closer to unleashing the full potential of soft robots. These include enhancements in actuator load capacity for carrying heavy components, improvements in the design of soft sensors for integrated feedback control, and streamlined or miniaturized on-board hardware that can eliminate the need for a tether. In this Review, we examine recent advances in actuation, sensing and subsystem integration, and place them in the context of functional untethered soft robotics.

Soft actuation

Actuation is one of the central challenges of achieving autonomous soft robots, and has been tackled with a wide variety of methods, including pneumatic actuation, thermal or photo-actuation, bio-hybrid actuation and electrical field actuation²⁰ (Fig. 2), which are described in detail below and summarized in Table 1.

Pneumatic actuation. Pneumatic and hydraulic actuators have long been popular among soft actuation methods thanks to their relatively large actuation forces, fast response times, high work densities and large strains (Table 1). Much recent work has focused on incorporating established pneumatic actuators into robotic locomotion^{21,22}, grasping²³ and wearable haptic²⁴ or assistive devices¹⁰.

Several groups have concentrated on improving the performance of such actuators, aiming to control radial expansion²⁵ or redirect deformation^{26,27} under applied pressure. Vacuums have also been employed to create strong contraction with minimal change in actuator radius²⁸ (Fig. 2a) and enable underwater gripping²⁹.

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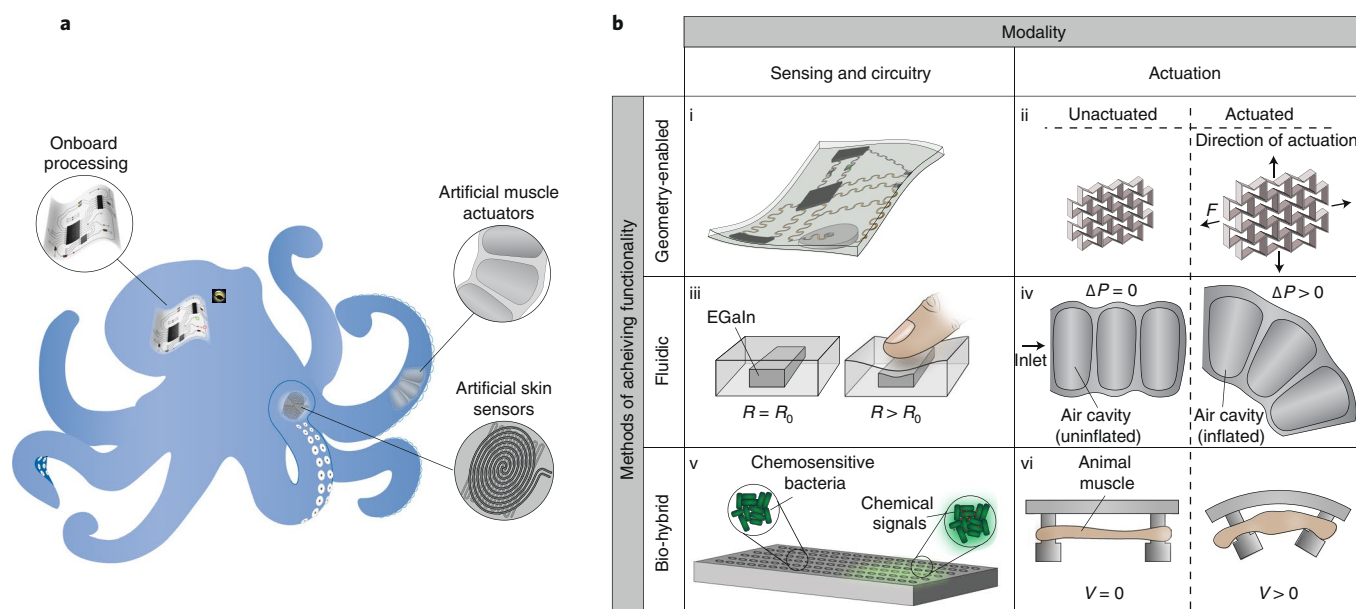


Fig. 1 | Overview of soft robotic systems. **a**, Conception of a future soft robot, inspired by current state-of-the-art octopus-inspired robots^{5,6}. This figure envisages the ways in which soft robotic technologies could be implemented in an advanced soft robot. **b**, Example methods of achieving circuitry and actuation for each generalized strategy (geometry-enabled, fluidic and bio-hybrid): (i) serpentine or wavy copper wiring between IC components that allow stretching; (ii) deterministic design of an auxetic metamaterial to create actuation in the *y*-direction in response to a force (*F*) in the *x*-direction; (iii) microfluidic sensing enabled by the change in cross-sectional area of an EGaIn microchannel, which causes the resistance (*R*) to increase from its initial value (R_0); (iv) pneumatic actuation caused by the asymmetric expansion of air cavities under pressure, where ΔP is the difference between pressure in the cavity and external pressure; (v) bio-hybrid sensing enabled by the luminescence of phyto-bacteria in response to chemical signals; and (vi) bio-hybrid actuation demonstrated when muscle cells contract under an applied voltage *V*.

Additionally, control systems have been developed in tandem with advancements in the mechanical properties of pneumatic muscles, with many groups incorporating pneumatic or liquid-metal microfluidic sensors into these actuators^{17,24–26}.

One limitation of pneumatic and hydraulic actuators is the requirement of an external pump to pressurize and depressurize the working fluid (Table 1). Although it is possible to place these components on board²², this hardware can limit the design and performance of untethered robots. Several groups have proposed innovative methods to circumvent the need for this equipment, effectively removing the pneumatic tether from these actuators. One group has developed a method to induce pneumatic contraction over a longer period (70 s) by evaporating ethanol via resistive heating³⁰, while others have employed combustion to achieve bending^{12,31}. Deformation in these functional air chambers can also be achieved through alternative methods such as electromagnetism, thereby enabling locomotion with minimal hardware³². These techniques effectively remove the pneumatic tether but introduce new challenges like slow response speed, reduced output force, or limited actuation control and timing.

Light actuation. Light can also be employed to induce a direct environmental response in an actuator (such as light regulation in a biomimetic iris³³ or heliotropism in an unpowered solar panel³⁴) or leveraged to create autonomous actuation with minimal hardware. For instance, Wani et al. positioned an optical fibre at the centre of a light-responsive liquid-crystal elastomer (LCE) to induce Venus Flytrap-inspired gripping in 0.2 s when a target object reflected the light back towards the LCE³⁵. Visible radiation has also been used to drive untethered, light-powered locomotion in LCEs^{36–38} (Fig. 2b) and hydrogels³⁹, and initiate gripping in copy paper-polypropylene bilayer actuators⁴⁰. This type of motion can sometimes be slow (with actuation times in the range of 0.1–1 s to minutes), and requires additional hardware to apply light to the actuators (Table 1).

Nevertheless, these actuators show promise for use in untethered, environmentally responsive soft robotic systems since they can react to changes in ambient light.

Combustion. Combustion is the exothermic reaction of a fuel in the presence of oxygen, which can release energy very slowly or very rapidly (that is, an explosion). Because of the high energy density of this fuel, there is little need for auxiliary power, yielding a unique range of applications that can lead to untethered robotic actuation. A number of untethered jumping robots have demonstrated the potential for combustion to power rapid, high-force actuation^{31,41,42}. Recently, combustion has also been employed to inflate and activate pneumatic actuators in a fully soft microfluidic robot¹² (see section ‘Systems-level integration’). Despite these advantages, the application of combustion to untethered soft robotics has been limited and further progress is required to achieve actuators and transmission systems capable of high cycle rates, long operational durations and a diverse variety of motions (such as contraction, bending and twisting).

Bio-hybrid actuation. With biomedical applications in mind, some groups have sought to improve the biocompatibility and stimuli-responsiveness of soft robotic systems by using biological materials as actuators^{43,44} (Fig. 2c). These bio-hybrid systems can incorporate muscle tissue, such as those engineered from the C2C12 line of mouse myoblasts, directly into soft systems^{17,45}. For these systems, actuation can be induced by applying electrical or optical impulses. These actuators show directional locomotion and can benefit from ‘exercise’ training, thus highlighting the ability of bio-hybrid machines to adapt to their environment⁴⁵.

Similarly, cardiac tissue engineered from the cardiomyocyte cells of a rat can be synchronized into spontaneous periodic contraction with electricity, a phenomenon that has been used to create untethered locomotion in a jellyfish-inspired robot¹⁸. More recently,

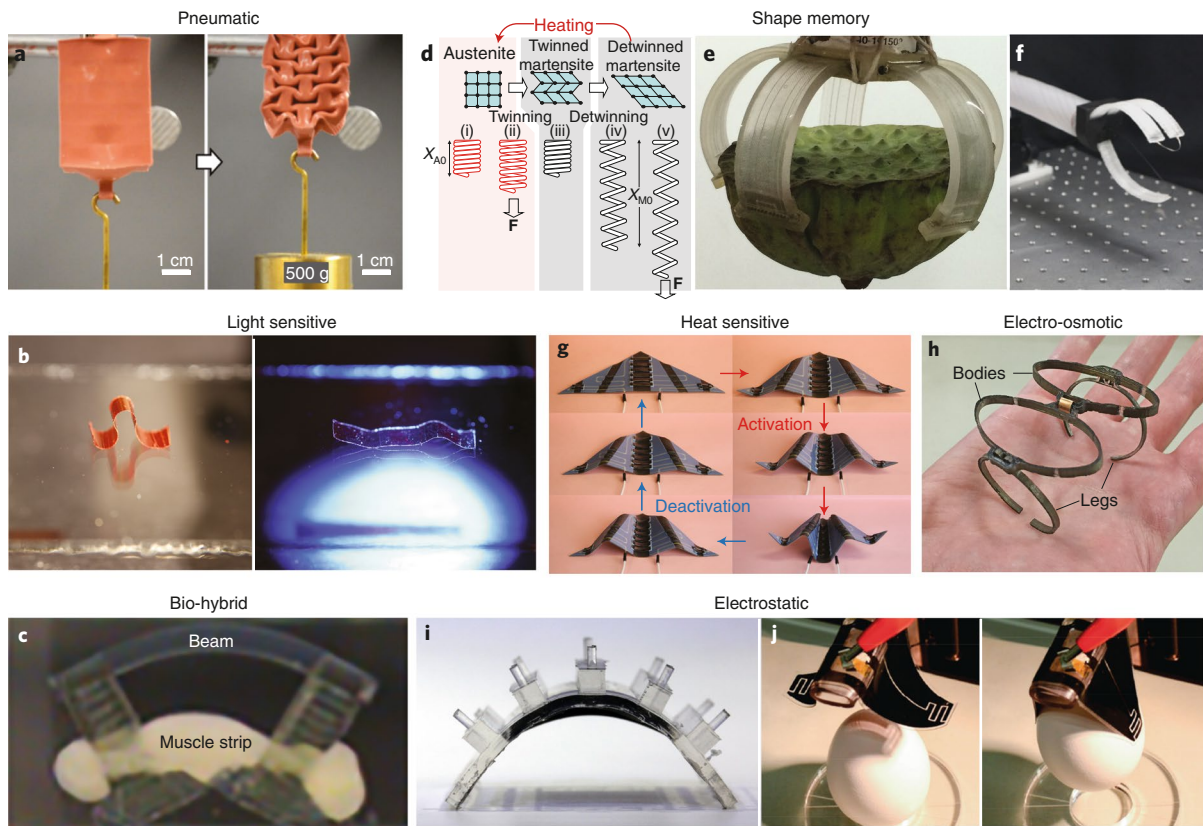


Fig. 2 | Methods of soft actuation. **a**, Vacuum-powered pneumatic actuator that creates contractile motion. **b**, A miniature LCE crawler (13 mm long) that moves in response to light. **c**, Bio-hybrid actuator (~4.6 mm long) with locomotion driven by electrically stimulated contraction of skeletal muscle. **d**, SMA spring, which contracts in response to resistive heating. In the diagram, **F** represents an applied force, while X_{A0} and X_{M0} represent the free length in the austenitic and martensitic spring, respectively. **e**, Modular gripper and walking robot actuated by resistive heating in an SMA. **f**, Gripper (100 mm long) actuated by resistive heating in a SMA. **g**, 3D-printed origami robot (110 mm side length) actuated by resistive heating in LCE hinges. **h**, Ionic polymer-metal composite-actuated caterpillar-inspired pipe crawling robot. **i**, Entirely soft, DEA-powered crawling robot (90 mm arc length). **j**, Dielectric elastomer actuator gripper, with increased gripping strength resulting from electrostatic adhesion. Credit: reproduced from ref. ²⁸, Wiley (**a**); ref. ³⁶, Wiley (**b**); ref. ¹⁷, National Academy of Sciences (**c**); ref. ⁵¹, IEEE (**d**); ref. ⁵², IOP (**e**); ref. ⁵⁶, Elsevier (**f**); ref. ⁵⁹, Royal Society of Chemistry (**g**); ref. ⁶¹, IEEE (**h**); ref. ⁶⁷, SPIE (**i**); ref. ⁷⁰, Wiley (**j**).

cardiomyocytes were employed to power a stingray robot, capable of phototactic navigation around obstacles⁴⁶. Other work has sought to control cell-attachment⁴⁷ and stability⁴⁸ in these machines to improve locomotion performance. Current progress in 3D bioprinting promises to facilitate further advances in bio-hybrid actuation⁴⁹.

While bio-hybrid machines currently allow for actuation in response to external stimuli (for example, applied electric field or light), there remains considerable work to be done before they can become fully autonomous and able to match the controllability and performance of other actuation methods (Table 1).

Table 1 | Comparison of soft actuation methods relevant to applications in untethered robots

Actuation method	Strain (%)	Work density (kJ m ⁻³)	Modulus (MPa)	Power density (kW m ⁻³)	Strain rate (% s ⁻¹)	Frequency (Hz)	Auxiliary equipment	Deformation type
Skeletal muscle	20–40	8–40	10–60	50–300	10–50	1–10	Body metabolism	Contraction
Pneumatic actuator	10–40	1–200	0.1–100	10–1,000	10–70	1–5	Pneumatic pump, valves	Contraction, bending, expansion
Liquid-crystal elastomer	10–50	1–50	0.1–3	0.01–10	1–10	0.001–1	Light or heat source	Contraction, bending
Bio-hybrid actuator	10–25	0.1–10	0.01–1	1–10	10–100	1–5	Biocompatible medium	Contraction
Shape-memory alloy	4–8	10⁴–10⁵	28–75 × 10 ³	10³–10⁵	10–50	0.5–5	Power supply	Contraction, bending
Ionic polymer-metal composite	0.5–10	1–10	25–2,500	0.01–1	1–3	0.1–2	Power supply	Bending
Dielectric elastomer actuator	1–1,000	100–500	0.1–3	10³–10⁵	10²–10⁵	1–100	Power supply	Bending, expansion

Bold denotes better performance. Bulky and more complex auxiliary equipment presents a significant challenge to untethered implementation.

Electrothermal actuation. Many of these non-electrical methods involve significant auxiliary equipment (that is, pneumatic pumps or light sources) that may be bulky⁵⁰ or are limited to passive environmental response and are thus difficult to control. Directly initiating actuation using electrical current with on-board batteries can overcome some of these limitations, bringing soft robotic systems closer to fully untethered functionality.

Electrically stimulated thermal methods have been used to activate smart materials like shape-memory alloys (SMAs) or thermoactive polymers. Nickel-titanium (nitinol) SMAs are a natural choice for soft actuation because they exhibit large, reversible bending deformations when they change from a martensite to austenite crystallinity, often in response to the resistive heating of the alloy. This transition can be leveraged for axial deformations when SMA actuators are coiled into springs⁵¹ (Fig. 2d). Since this phase transition is based on temperature, heat storage in the alloy and its matrix typically limits the deactivation speed and, therefore, the response frequency of SMAs. Recent work has achieved SMA-powered locomotion, addressing this problem of overheating by precisely controlling the voltage applied to the SMA⁵² (Fig. 2e), employing active cooling with water⁵³ or air⁵⁴, or maximizing the heat dissipation by incorporating a thermally conductive soft elastomer⁵⁵ (Fig. 2f). Other work has employed SMAs in an elastomeric matrix to create improved gripping^{52,56} and untethered biomimetic locomotion⁵⁷.

Employing resistive heating in SMAs circumvents the need for external heating equipment; similarly, resistive heating can be incorporated into any conductive or non-conductive thermally activated material, inducing thermal expansion⁴⁰, phase or glass transition⁵⁸, or LCE phase transition⁵⁹. These methods have been used for gripping⁴⁰, origami⁵⁹ and locomotion⁵⁹ (Fig. 2g). Such approaches are promising for many types of untethered systems, but these actuators do pose challenges for high-duty-cycle or high-frequency applications because of the significant power consumption and heat production of electrothermal actuation (Table 1).

Electrical actuation. Compared with electrothermal actuators, electroactive polymer composites such as ionic polymer–metal composites (IPMCs) require less power input and do not generate heat when stimulated. IPMCs are composed of an ionic polymer surrounded by noble metal electrodes, and activate under a small voltage. When water flows to balance the migration of ions toward the cathode, the actuator swells near the cathode, causing the actuator to bend. Because these deformations are typically small, IPMC actuators are best suited for applications that require modest actuation (Table 1). For this reason, they have been proposed for use in applications such as intraocular lenses⁶⁰ and inchworm-inspired robots, in which leg pairs and internal body segments are alternately actuated⁶¹ (Fig. 2h). Well-suited for underwater applications, IPMCs were also recently applied to an untethered, steerable fish⁶².

Another class of electroactive polymers is the dielectric elastomer actuator (DEAs), which uses large electric fields to deform elastomeric materials sandwiched between two compliant electrodes. Recent work has sought to use these materials for soft robotic locomotion (Fig. 2i) because of their fast response times and low power requirements^{63–68} (Table 1). Underwater, the weight is balanced by the buoyant force and the water can be used as an electric ground, thereby enabling high payload⁶⁴ and even untethered swimming⁶⁵. When combined with other actuators, such as stiffness-tuning components⁶⁹ or electrostatic adhesives⁷⁰ (Fig. 2j), the maximum achievable force is increased, enabling significantly higher gripper loads. Some work with DEAs has leveraged their simple structure to create all-soft switches, oscillators and robots that crawl with a simple d.c. input⁶⁷. Overall, these actuators perform very well across many metrics, particularly in response speed and power density. As their output force and stroke continue to improve, these actuators have strong potential for further applications in untethered systems (Table 1).

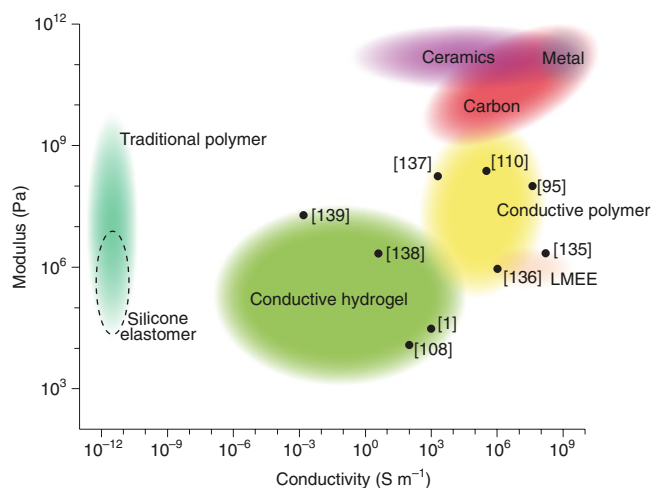


Fig. 3 | Modulus and conductivity of various materials in soft robotics.

The points on the plot represent the compliance and conductivity of the adjacent numbered references.

Artificial skin electronics

To sense environmental stimuli and control soft actuators, researchers have worked on a variety of methods to incorporate electronics into soft structures. Historically, there has been a trade-off between compliance and conductivity: highly conductive materials, such as metals, have a high Young's modulus, while compliant materials, such as elastomers, have a low conductivity⁷¹ (Fig. 3). Producing conductive materials with high compliance has been a major challenge in soft robotics, and is addressed by many of the methods described below.

Deterministic and ultrathin structures. By reducing the thickness of stiff materials and arranging them into elastically deformable structures, it is possible to achieve meso- and macroscale compliance across a wide range of materials, including those found in traditional electronics (such as copper)⁷². Examples of deterministic patterns range from serpentine circuit wiring, spring-like coils and meshes to truss-like and tessellated structures (for example, origami).

These thin patterned circuits have been integrated into a variety of different sensing schemes to acquire reliable biomedical data, using mechano-acoustic sensors to detect heart murmurs⁷³, optical sensors to measure blood flow, oxygenation or ultraviolet radiation dosage^{74,75} (Fig. 4a), electrophysiological sensors to measure heart, muscle, eye or brain activity⁹, and strain sensors to determine hand gestures⁷⁵ (Fig. 4b). Many of these designs incorporate pre-packaged integrated-circuit (IC) chips^{9,73–75}, but for some applications the deterministically patterned materials can serve as circuit components themselves. Employing ultrathin films (roughly 1 μm thick) has enabled the creation of cheap and robust transistors⁷⁶, tactile sensors⁷⁶ and LEDs⁷⁷ that can be crumpled without losing functionality⁷⁶. In one study, ultrathin organic field-effect transistors were integrated with organic electrochemical transistors (OECTs) to create an intrinsically flexible electrophysiology array⁷⁸ (Fig. 4c).

Thin and deterministic structures are not only applicable to stretchable and flexible circuits, but have also been used to transfer electronics onto non-developable (for example, spherical) surfaces⁷⁹, including a contact lens with integrated microelectronics⁸⁰ (Fig. 4d). While ultimately constrained by the strain limit of the stiff internal materials, these circuits can interface well with existing devices, thereby enabling advanced sensing capabilities in soft circuits. Some work has taken steps towards untethered battery-free circuitry by employing near-field communication (NFC) schemes to provide power and transmit data^{74,80}. Other groups have

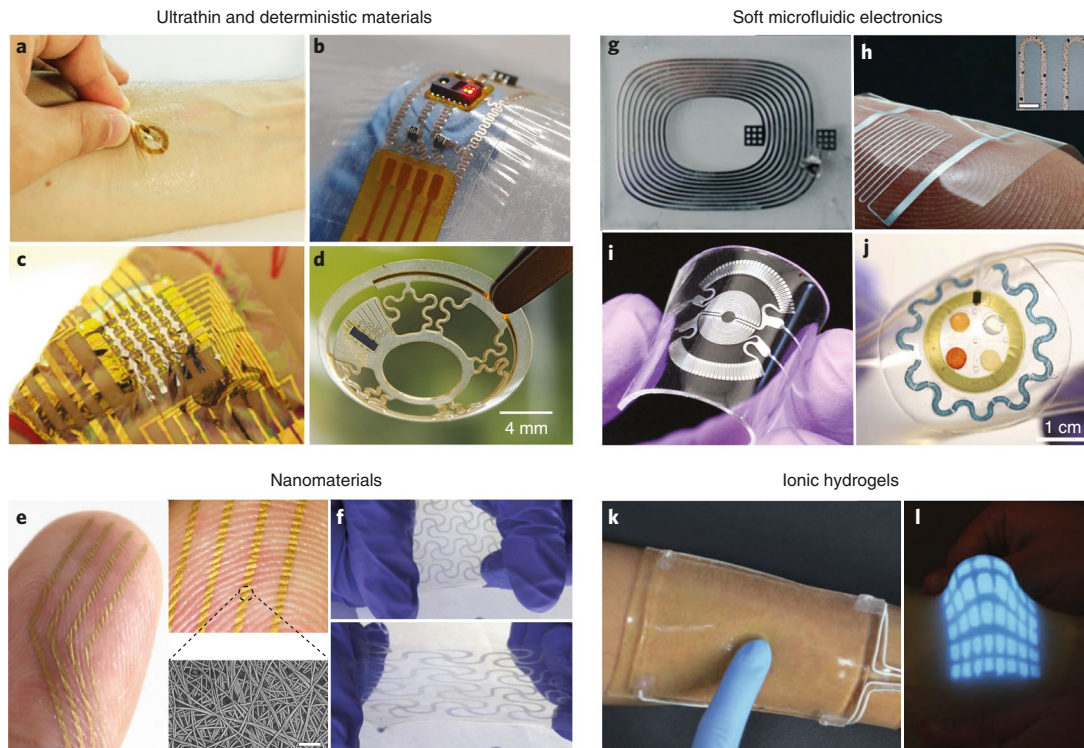


Fig. 4 | Advances in soft sensing, conductivity and artificial skin. a–d, Sensors fabricated from ultrathin and deterministic architectures. **e,f,** Conductive soft structures achieved by structured nanomaterials. Scale bar in **e**, 5 μm . **g–j,** Conductive and wearable devices enabled by microfluidics. Scale bar in **h**, 5 mm. **k,l,** Wearable devices enabled by ionic hydrogel electronics. Specifically, these include: a mechano-acoustic on-skin sensor (**a**); a wearable device to measure electrophysiological signals and strain (**b**); an organic field-effect transistor/organic electrochemical transistor-enabled electrophysiology sensor array (**c**); a contact lens with integrated electronics (**d**); on-skin conductive traces that can measure strain and muscle activity (**e**); a highly stretchable PEDOT:PSS film applicable to transistor circuits (**f**); an EGaIn coil antenna fabricated by vacuum filling (**g**); a biphasic thin film of gold and gallium (**h**); a highly sensitive EGaIn-enabled pressure sensor (**i**); a colourimetric wearable patch for sweat analysis (**j**); a soft touch panel made from ionic hydrogels (**k**); and a stretchable LED array composed of 4 mm \times 4 mm pixels, created from hydrogel and ZnS-doped dielectric elastomer (**l**). Credit: reproduced from ref. ⁷⁴, AAAS (**a**); ref. ⁷⁵, Wiley (**b**); ref. ⁷⁸, Wiley (**c**); ref. ⁸⁰, Wiley (**d**); ref. ¹³⁹, Macmillan Publishers Ltd (**e**); ref. ⁹⁷, AAAS (**f**); ref. ¹⁰⁴, Royal Society of Chemistry (**g**); ref. ¹⁰⁵, Wiley (**h**); ref. ¹⁰⁶, Wiley (**i**); ref. ¹¹², AAAS (**j**); ref. ¹¹³, AAAS (**k**); ref. ⁷, AAAS (**l**).

demonstrated untethered wearable devices by powering electronics and Bluetooth using lactate from human sweat⁸¹.

Nanomaterials and conductive elastomer composites. Another way to engineer stretchable circuits is to embed soft materials with conductive nanofilms or percolating networks of conductive nano/microparticles. The electrical resistance of these materials is dependent on the contact area between particles, which can vary with deformation. As a result, nanomaterials can be made into robust resistive strain or pressure sensors^{82–85}, and can thus be used to locate applied stress⁸⁶. These sensors are often well-suited for wearable devices and can be used to determine end-effector position and joint angles⁸⁷, or to translate the American Sign Language alphabet⁸⁸. Mesh structures formed from gold and polyvinyl alcohol can be fabricated directly onto the skin, thereby ensuring gas-permeability while forming conductive traces and sensors that can measure finger bending and muscle activity⁸² (Fig. 4e).

Silver nanowires are particularly useful as fillers given their high electrical conductivity, and can be incorporated into elastomers to form stretchable electrodes^{89–91} or even LEDs⁸⁹. Graphene sheets and graphene nanoscrolls are also effective for enabling conductivity in elastomers under high strain⁹². Many of these filled conductive elastomers also exhibit high transparency and may be useful in optical applications^{89,92,93}.

Capacitive pressure sensors can also be created by deforming a dielectric layer between electrodes constructed from these

materials^{90,93}. Recent work has incorporated microstructures into such electrodes to increase deformation at low pressures and dramatically improve sensitivity, yielding easy-to-fabricate, highly sensitive, wearable pressure sensors capable of measuring vocal vibration and air flow⁹⁰.

Furthermore, owing to the inherent conductivity of these materials, the fabrication of simple sensors is both scalable and robust using a variety of techniques, including screen printing^{87,94}, direct writing^{94,95} and spray deposition⁹⁶. Sencadas et al. developed a conductive ink that can be sprayed directly on soft materials to function as a piezoresistive strain sensor, without the need for encapsulation⁹⁶.

Conductive ionomer composites provide an alternative method of achieving isotropic conductivity. Recent work on combining poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) with additives for enhanced conductivity and stretchability have resulted in deformable conductors that can support high strain (600%) and conductivity (4,100 S cm⁻¹). Such materials can be used to engineer circuits that are semi-transparent⁹³ and contain field-effect transistors and other rigid, surface-mounted components⁹⁷ (Fig. 4f). Because of their lightness, compliance and broad functionality, these circuits show strong potential for integration in untethered systems.

Fluid elastomer systems. Alternatively, conductivity can be achieved without employing any stiff materials or fillers, thereby reducing internal stresses and maximizing stretchability. Liquid metals such

as mercury, gallium–indium–tin (galinstan) and eutectic gallium–indium (EGaIn), can provide conductive pathways in the absence of stiff materials. Microchannels of these materials embedded in flexible and stretchable elastomers can be used to create intrinsically soft sensors⁹⁸ or connect pre-packaged IC components⁹⁹. EGaIn is particularly desirable for these applications because of its high conductivity, stable surface oxides, low toxicity and low viscosity¹⁰⁰.

The fabrication and filling of these liquid-metal microchannels has been a persistent challenge, with numerous techniques proposed in the literature, including injection¹⁰¹, freeze placement¹⁰² and direct writing¹⁰³. Recent work has demonstrated fast and accurate filling of complex microchannel geometries via a vacuum¹⁰⁴ (Fig. 4g), as well as the fabrication of biphasic thin films by sputtering gold and thermally evaporating liquid gallium¹⁰⁵ (Fig. 4h). Several techniques have also focused on forming liquid-metal interconnects between IC devices¹⁰⁵.

Because of the inherent compliance of these materials, liquid metal elastomer systems are ideal for sensing in fully soft applications^{83,106}, such as gloves. These devices can be used for inertial sensing⁸³ or pressure sensing for tactile feedback and pulse monitoring¹⁰⁶ (Fig. 4i), building on designs introduced by Majidi and Park et al.⁹⁹. They are also useful in sensing strain in pneumatic systems, since they refrain from using stiff components^{23,107,108}, and can even be used in transparent devices¹⁰⁹. As with the deterministic approach, some of these devices take explicit steps towards untethered functionality by incorporating NFC features to output sensor data wirelessly⁸³.

Beyond standard electronic components, soft microfluidics can be applied to wearable and untethered robotic devices in other ways as well. Perspiration pressure¹¹⁰, rate¹¹¹ and composition¹¹² can be determined using microfluidic patches that attach to the skin, showing colourimetric analysis that requires no external connection (Fig. 4j). Another application of microfluidic logic for soft robotics was introduced by Wehner et al. for a self-regulating oscillator that employs controlled combustion for the pneumatic actuation of soft robotic limbs¹².

Conductive gels. Gels provide another set of materials to construct soft circuits and electronic devices. When filled with ionic solution, they can serve as highly stretchable conductors that can conform to arbitrary geometries. This enables highly compliant devices that exploit bulk conductivity, such as soft touch panels¹¹³ (Fig. 4k), underwater DEAs⁶⁵, pulse and respiration sensors¹¹⁴, and even stretchable electroluminescent displays and sensors⁷ (Fig. 4l).

Hydrogels are water-filled gels that are biocompatible and can operate in wet or high-humidity conditions. This feature, which could be useful for in vivo applications, permits them to absorb and analyse sweat¹¹² and tune the dosage of drugs at controlled rates¹¹⁵. They can also incorporate rigid IC components and wavy interconnects, which allows hydrogel systems to blend electronic sensing with chemical activation¹¹⁵. Recent work has further improved the integration of such circuit components, demonstrating hydrogel self-healing and enhanced bonding between tough hydrogels and a wide variety of other materials. This work enables stretchable batteries, adaptive lenses and energy-harvesting devices¹¹⁶, and reveals the utility of these materials in untethered systems.

Systems-level integration

There have been a number of studies investigating the efficacy of various artificial muscle actuators into soft robotic systems. Referring to Fig. 5, these include implementations that contain SMAs^{54,55} (Fig. 5a,b), DEAs^{63,68,117} (Fig. 5c–e), pneumatics³² (Fig. 5f), and LCEs³⁵ (Fig. 5g). Despite encouraging progress in soft actuation and electronics, there have only been a few forays into fully untethered soft robots. Developing actuators powerful enough to carry their power supply and processing requirements is a major

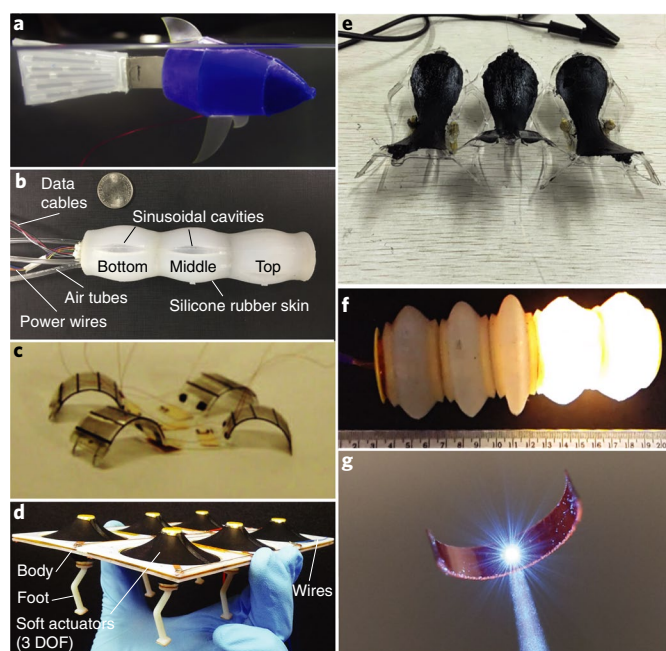


Fig. 5 | Implementation of soft actuators into robotic systems. **a**, SMA-actuated fish (20 cm long). **b**, SMA-actuated peristalsis robot (13.9 cm diameter). **c**, Fast DEA-actuated walker (6 cm). **d**, A multi-degree-of-freedom (DOF) DEA-powered walker. **e**, Differential friction, DEA-powered annelid robot (17 cm). **f**, Electromagnetically actuated pneumatic worm-robot. **g**, Venus flytrap-inspired, LCE-actuated gripper (5 mm). Credit: reproduced from ref. ⁵⁵, National Academy of Sciences (**a**); ref. ⁵⁴, IEEE (**b**); ref. ⁶³, IEEE (**c**); ref. ⁶⁸, Elsevier (**d**); ref. ¹¹⁷, IOP (**e**); ref. ³², Mary Ann Liebert (**f**); ref. ³⁵, Macmillan Publishers Ltd (**g**).

challenge to cutting the cord, which some groups have addressed by employing more traditional actuation methods in soft systems or by significantly scaling up their actuators. For instance, Malley et al. employed a simple cable drive to develop an untethered flipping soft robot that could climb Velcro surfaces¹¹⁸ (Fig. 6a), while Tolley et al. created a 0.65-m-long pneumatic robot capable of carrying batteries, compressors, valves and microprocessors²² (Fig. 6b).

Many other untethered soft robots take advantage of marine environments to circumvent static friction and offload the mass of their auxiliary components^{57,62,119,120}, thereby improving the system efficiency¹²¹. These principles allowed the autonomous soft robotic fish developed by Marchese et al. to benefit from its large size and incorporate hydraulic actuators and power within its body cavity^{119,120} (Fig. 6c). Researchers using hydrogel DEAs have similarly capitalized on buoyancy to create a fast-moving untethered fish with a built-in high-voltage supply⁶⁵ (Fig. 6d).

Compared with aquatic locomotion, terrestrial locomotion requires a greater force to transport the same mass. Weight can be minimized by employing direct activation methods, like SMAs, which require notably less auxiliary equipment, allowing for small terrestrial robots with on-board power and processing^{57,122,123} (Fig. 6e,f). Inversely, output force can be maximized, as seen in several studies using combustion to create untethered jumping robots^{31,42,124} (Fig. 6g,h). More recently, controlled combustion has been employed to create an electronics-free, untethered soft octopus¹² (Fig. 6i).

Similarly, several groups have created untethered sensor systems by dispensing with the need for on-board power entirely, thus circumventing the challenge of shrinking their electrical components. This comes either in the form of electronics-free, microfluidic sensors^{110–112}, or NFC induction coils that can briefly power wearable devices with electromagnetic waves in order to allow sensor

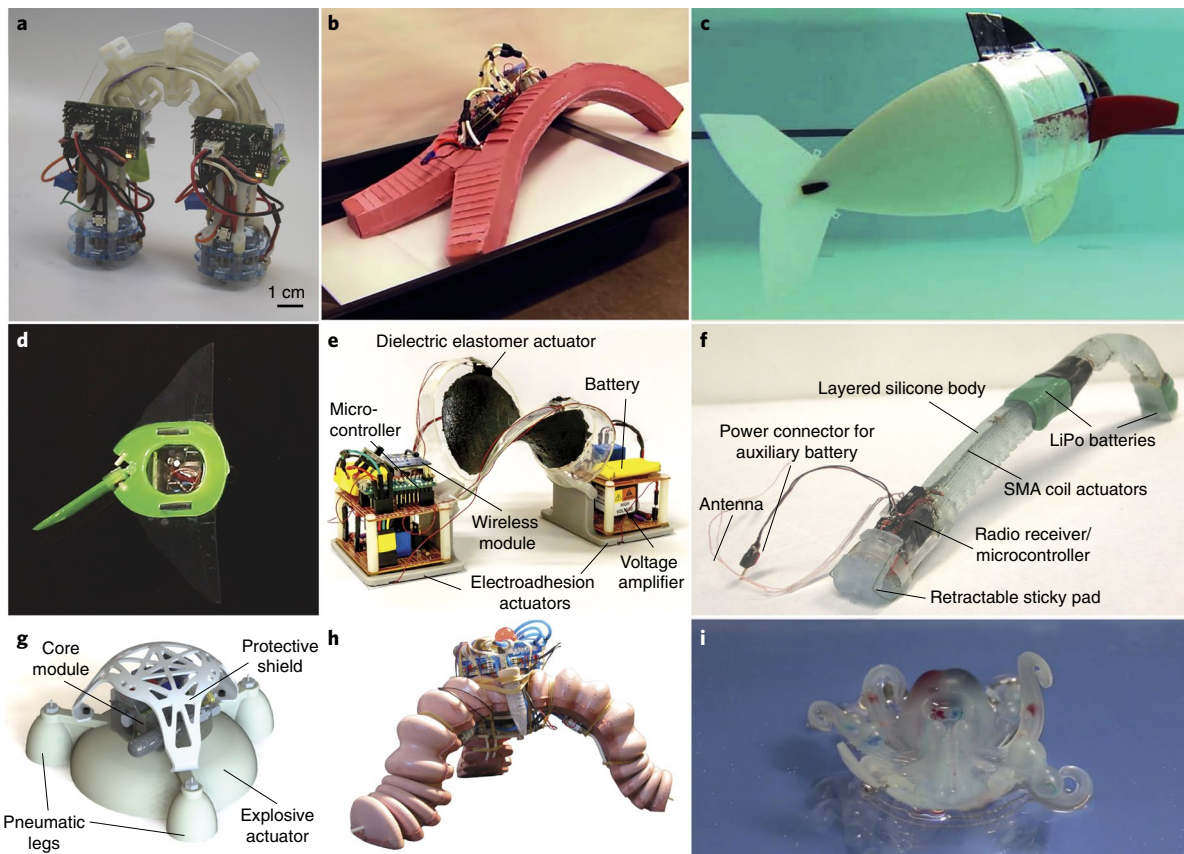


Fig. 6 | Fully untethered robotic systems. **a**, Climbing robot powered by a motor-cable system. **b**, Robust walking robot powered by on-board pneumatics (65 cm long). **c**, Biomimetic swimming robot powered by a hydraulic actuation system (35 cm long). **d**, Ray-inspired swimming robot powered by DEAs (9.3 cm long). **e**, Electro-adhesive walking robot powered by DEAs. (17 cm outer diameter) **f**, Caterpillar-inspired multi-gait robot powered by SMAs (10 cm long). **g**, Jumping robot powered by combustion (12.6 cm tall; 30 cm radius). **h**, Jumping robot with controllable orientation powered by combustion (8 cm tall; 15 cm radius). **i**, Octopus robot powered by combustion and controlled by fluidic logic (~55 mm). Credit: reproduced from ref. ¹¹⁸, IEEE (**a**); ref. ²², Mary Ann Liebert (**b**); ref. ¹¹⁹, Mary Ann Liebert (**c**); ref. ⁶⁵, AAAS (**d**); ref. ¹²³, SPIE (**e**); ref. ¹²², IOP (**f**); ref. ⁴², AAAS (**g**); ref. ³¹, IEEE (**h**); ref. ¹², Macmillan Publishers Ltd (**i**).

readings to be taken^{74,83}. In terms of actuation, some bio-hybrid devices can eliminate the need for tethers because their motion can be controlled by applying small electrical charges to the environment¹⁸. Alternatively, components for power delivery can be engineered to be more lightweight and flexible in order to improve the portability of untethered soft devices. Recent work includes stretchable batteries^{116,125} and elements that generate power by harvesting sweat in a stretchable electronic-skin-based biofuel cell⁸¹, incorporating flexible photovoltaics into a skin-conformal layer¹²⁶ or including thin stretchable triboelectric nanogenerators¹²⁷.

In general, the difficulty of creating completely untethered robotic systems arises from issues in materials compatibility and integration. Integrating soft actuation, sensing and circuitry with microelectronics and other miniaturized rigid hardware introduces unique challenges in fabrication and interfacing. Some groups have worked to improve integration by unifying the fabrication of actuators and sensors¹²⁸, while others have sought to introduce transitions in material stiffness that reduce the stress concentrations caused by impedance mismatches between stiff and soft components^{129–131}. Further progress can also be accomplished through advancements in functionally graded materials and digital multimaterial 3D printing⁴², as well as improvements in soft-matter functionality that decrease reliance on rigid hardware.

Current challenges

Despite these exciting developments across a wide variety of subfields, there still remains considerable work to be done before

reliable, untethered functionality in soft robotics can be achieved. Improvements in hardware for actuation, sensing and on-board electronics will likely drive the development of these systems. However, further progress will also increasingly depend on advancements in feedback control, machine intelligence and computational modelling. In general, we anticipate that new developments in soft robotics engineering will be driven by three primary thrusts: materials improvement, materials integration, and intelligence and autonomy.

Materials improvements. Progress in soft systems will require research into new multifunctional materials, composites and structures/layouts. While incremental improvements continue to increase the stretchability, electrical conductivity and sensing ability of these material systems, future work will focus on a broader range of advanced functionalities. This includes the ability to tune the rigidity of materials, in order to enable quick and reversible switching between a soft/compliant state and a stiff/load-bearing state⁵⁸. Such materials will bridge the gap between soft and conventional robotics, offering either stability and load-bearing strength or compliance and versatility as the situation demands¹³². Additionally, because of the susceptibility of soft systems to damage, it will be important for robots and circuits to be constructed from tough and self-healing materials, including tear-resistant elastomers based on biological systems^{133,134}. Ideally, these materials will exhibit a fracture toughness of more than 10 kJ m⁻², and will be able to withstand or self-repair when subject to mechanical or electrical damage. These capabilities

will improve the robustness of soft systems, making them practical for use in harsh and unpredictable applications. Furthermore, as soft systems become more complex, efficient heat management will become critical to designing functional soft electrical components. Creating and integrating soft thermally conductive materials⁵⁵ and polymers will help enable these advances. Finally, as these efforts produce increasingly mobile soft robots, research into their environmental impact (for example, using biodegradable structural materials¹³⁵) should also be pursued.

Materials integration. Improving the means by which these materials and architectures are combined will also contribute to more complex functionality or increased performance of integrated soft systems. Enhanced prototyping methods that rapidly integrate soft elastomers, fluids, biomaterials and electronics into complex 3D structures (for example, two-photon polymerization, multi-material printing and laser sintering) can accelerate progress across a wide variety of soft robotic designs and material architectures. Furthermore, developing methods to minimize cost and maximize scalability can increase the speed and viability of mass production. These advances can extend beyond simply expediting the production of current technologies. Introducing methods for multi-material or multiple length-scale fabrication will ultimately usher in new soft robotic components and functionalities.

As the capabilities of these components expand, the mechanical and electrical interfaces that appear throughout soft devices become increasingly important. While the prospect of fully soft circuits (for example, integrating soft batteries or soft IC components) is alluring, it may be more fruitful in the short term to improve the interfacing between stiff, conventional components and compliant systems. Because deterministic methods for achieving stretchable functionality use materials with similar mechanical and electrical properties to pre-packaged IC chips, they may provide the most robust connection to these components. However, fluid-elastomer hybrids have greater intrinsic compliance, thus improvements to the IC interface may yield more robust and highly stretchable circuits. Finding a way to achieve functional stiffness gradients easily within these soft materials may help such hybrid materials achieve greater mechanical and electrical stability under strain.

Additionally, synthetic biology¹⁹ provides us with a means of creating biosensing bacteria or ‘artificial cells’ that can be programmed to respond in unique ways to external signals. Synthetic bacteria (for example, genetically modified *E. coli*) may be engineered to express fluorescent or luminescent proteins in response to chemical stimulation. More broadly, there remain many opportunities to achieve unique bio-hybrid functionality by incorporating engineered cells and biomaterials into soft robotic systems. Potential applications range from chemical sensing to ‘living machines’ capable of energy harvesting, metabolism/conversion and material synthesis. Developing ways to interface with these types of biological systems will be important in reaching the next stage of soft functionality. Existing work on the incorporation of biological materials into soft systems hints towards near-future electronic-biological hybrid technologies like neurons-on-a-chip or soft robot-brain interfaces.

Intelligence and autonomy. In addition to reshaping mechanical compliance and functionality, the use of soft materials also has profound implications on how robots are modelled and controlled. In contrast with autonomous vehicles, humanoid robots and other piecewise rigid systems that have finite degrees of freedom, soft-matter machines and robots are continuous elastic bodies that exhibit infinite degrees of freedom. This introduces new challenges in sensing and proprioception, feedback and adaptive control, path planning and robot intelligence that go beyond the scope of conventional algorithms for robotic autonomy. In most cases, soft

robots will be ‘unobservable’, with incomplete information about their dynamical state and surface interactions. Instead, sensor data will have to be combined with data-driven learning algorithms and computational modelling based on physics engines and finite-element techniques. For more complex systems, this fusion of statistical and physics-based approaches will require advancements in on-board, distributed or cloud-based processing so that the soft robot can make decisions in real-time.

In some cases, soft robot intelligence and autonomy can be aided by ‘morphological computing’, in which signals are processed mechanically through elastic deformation, acoustics or other physical material responses^{136,137}. A simple example is the way that a ‘universal’ granular jamming actuator¹³⁸ autonomously deforms and adapts to the shape of a 3D object — a task that, for a highly articulated piecewise rigid robotic system, would require considerable sensing and digital processing. Near-term efforts can generalize these principles to a broader range of processing tasks by exploring related mechanisms in soft electromechanical transducers (for example, dielectric elastomers and liquid-metal microfluidics) and photonic and acoustic metamaterials.

Conclusions

The past few years have brought many exciting developments to the field of soft robotics. New approaches in sensing and actuation, new materials and material architectures, and dramatic improvements in existing technologies have yielded highly functional soft devices and robots. As we push towards practical, untethered systems, improvements in robustness, sensitivity, strength and efficiency become increasingly important. Simultaneously, mechanisms for efficient fabrication and precise control of soft robots promise to make these cordless systems feasible and cost-effective. In the near future, advances in the field will begin to yield new consumer, healthcare and industrial technologies that will have a transformative impact on how we interact with machines and electronics. Such advancements will require continued progress in soft multifunctional materials as well as breakthroughs in bio-hybrid engineering and modelling, controls and machine intelligence for soft robot autonomy.

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Author contributions

S.I.R. compiled the references and wrote the manuscript. C.M. and R.J.W. conceived and structured the paper. All authors contributed to editing and reviewing.

Competing interests

The authors declare no competing financial interests.

Additional information

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