Untethered soft robotics

Article *in* Nature Electronics · February 2018

DOI: 10.1038/s41928-018-0024-1

3 authors:

Steven Rich
Carnegie Mellon University

Robert J. Wood
Harvard University

Carmel Majidi
Carnegie Mellon University

REVIEW ARTICLE
https://doi.org/10.1038/s41928-018-0024-1

nature electronics

Untethered soft robotics

Steven I. Rich[1], Robert J. Wood[2] and Carmel Majidi[1]*

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 electronics[4] 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 monitoring[9] 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 demonstrated[12], 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 actuation[20] (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], grasping[23] and wearable haptic[24] or assistive devices[10].

Several groups have concentrated on improving the performance of such actuators, aiming to control radial expansion[25] or redirect deformation[26,27] under applied pressure. Vacuums have also been employed to create strong contraction with minimal change in actuator radius[28] (Fig. 2a) and enable underwater gripping[29].

[1]Integrated Soft Materials Laboratory, Carnegie Mellon University, Pittsburgh, PA, USA. [2]Harvard Microrobotics Lab, Harvard University, Cambridge, MA, USA. *e-mail: cmajidi@andrew.cmu.edu

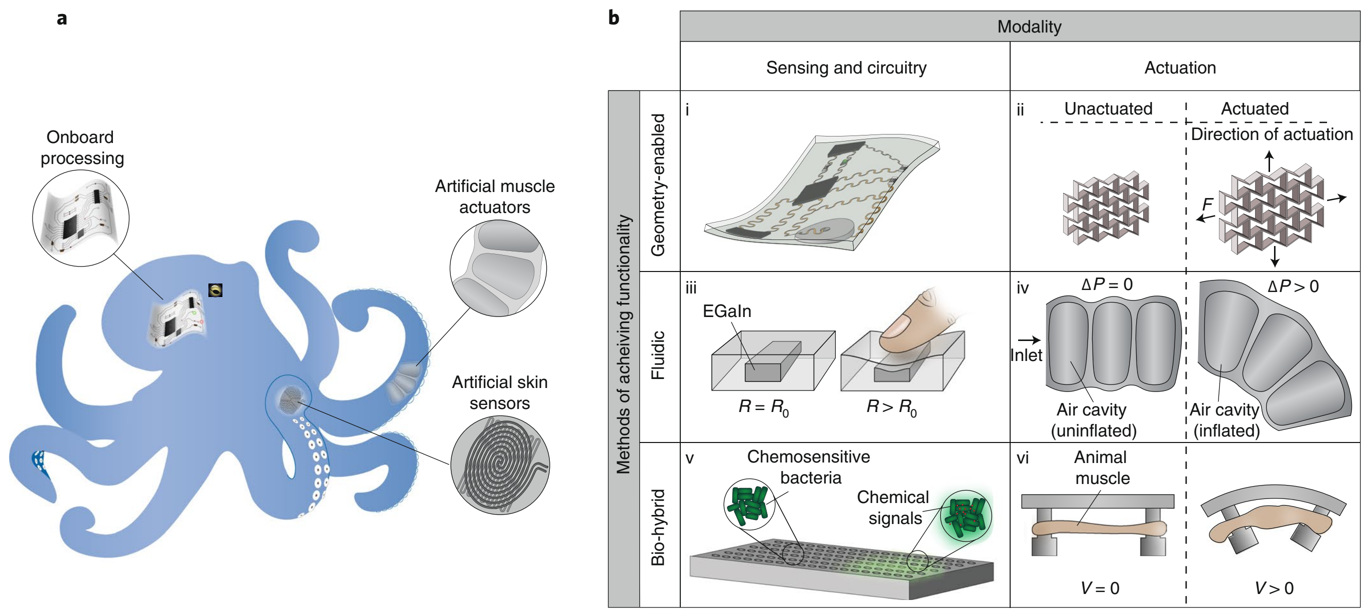

Fig. 1 | Overview of soft robotic systems. a, Conception of a future soft robot, inspired by current state-of-the-art octopus-inspired robots[5,6]. This figure envisages the ways in which soft robotic technologies could be implemented in an advanced soft robot. **b**, Example methods of achieving circuitry 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 phytobacteria 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 board[22], 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 heating[30], 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 hardware[32]. 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 iris[33] or heliotropism in an unpowered solar panel[34]) 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 LCE[35]. Visible radiation has also been used to drive untethered, light-powered locomotion in LCEs[36–38] (Fig. 2b) and hydrogels[39], and initiate gripping in copy paper-polypropylene bilayer actuators[40]. 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 robot[12] (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 environment[45].

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 robot[18]. More recently,

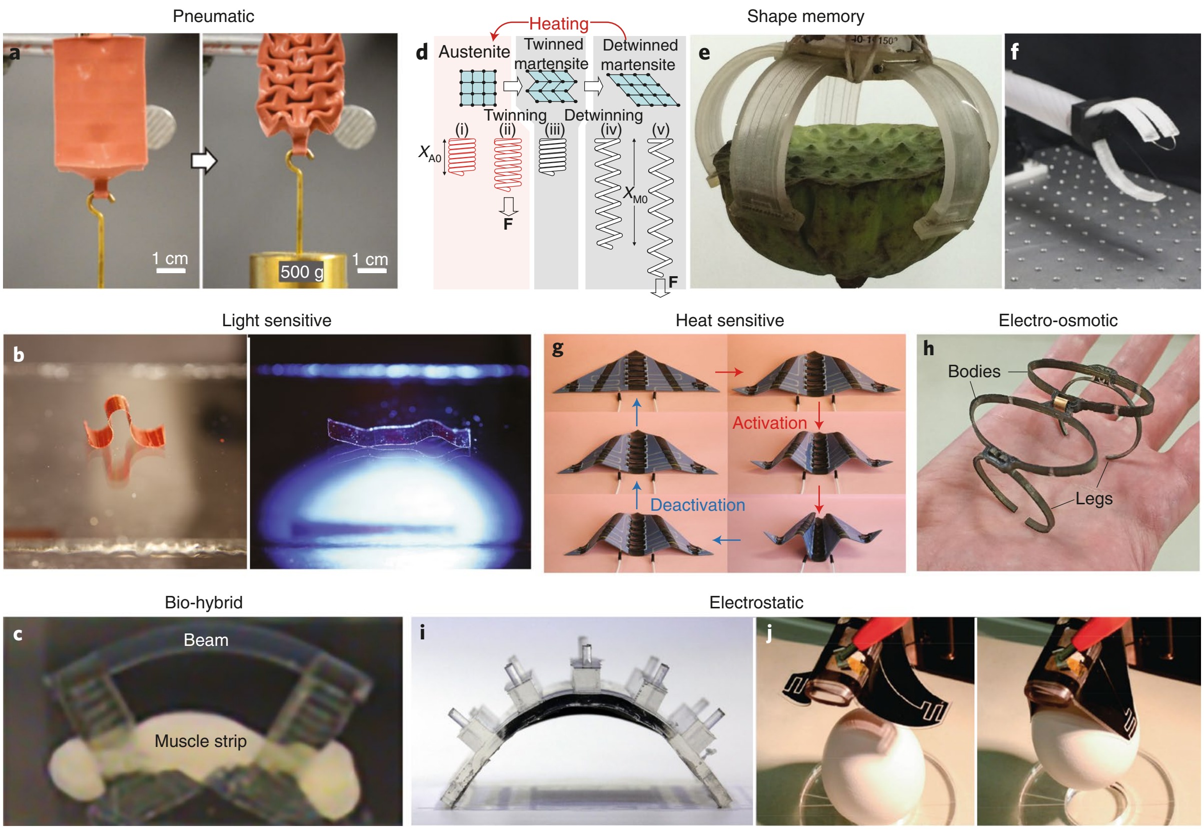

Fig. 2 | Methods of soft actuation. a, Vacuum-powered pneumatic actuator that creates contractile motion. **b**, A miniature LCE crawler (13 mm long) that moves in response to light. **c**, Bio-hybrid actuator (~4.6 mm long) with locomotion driven by electrically stimulated contraction of skeletal muscle. **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 obstacles[46]. Other work has sought to control cell-attachment[47] and stability[48] in these machines to improve locomotion performance. Current progress in 3D bioprinting promises to facilitate further advances in bio-hybrid actuation[49].

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	**10^4–10^5**	28–75 × 10^3	**10^3–10^5**	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 acutator	**1–1,000**	100–500	**0.1–3**	**10^3–10^5**	**10^2–10^5**	**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 bulky[50] 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 springs[51] (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 SMA[52] (Fig. 2e), employing active cooling with water[53] or air[54], or maximizing the heat dissipation by incorporating a thermally conductive soft elastomer[55] (Fig. 2f). Other work has employed SMAs in an elastomeric matrix to create improved gripping[52,56] and untethered biomimetic locomotion[57].

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 expansion[40], phase or glass transition[58], or LCE phase transition[59]. These methods have been used for gripping[40], origami[59] and locomotion[59] (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 lenses[60] and inchworm-inspired robots, in which leg pairs and internal body segments are alternately actuated[61] (Fig. 2h). Well-suited for underwater applications, IPMCs were also recently applied to an untethered, steerable fish[62].

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 payload[64] and even untethered swimming[65]. When combined with other actuators, such as stiffness-tuning components[69] or electrostatic adhesives[70] (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. input[67]. 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).

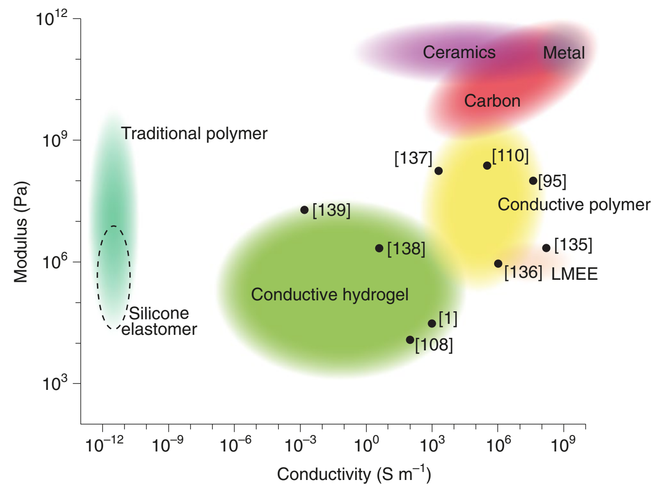

Fig. 3 | Modulus and conductivity of various materials in soft robotics. The points on the plot represent the compliance and conductivity of the adjacent numbered references.

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 conductivity[71] (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 pattered circuits have been integrated into a variety of different sensing schemes to acquire reliable biomedical data, using mechano-acoustic sensors to detect heart murmurs[73], optical sensors to measure blood flow, oxygenation or ultraviolet radiation dosage[74,75] (Fig. 4a), electrophysiological sensors to measure heart, muscle, eye or brain activity[9], and strain sensors to determine hand gestures[75] (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 transistors[76], tactile sensors[76] and LEDs[77] that can be crumpled without losing functionality[76]. In one study, ultrathin organic field-effect transistors were integrated with organic electrochemical transistors (OECTs) to create an intrinsically flexible electrophysiology array[78] (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) surfaces[79], including a contact lens with integrated microelectronics[80] (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

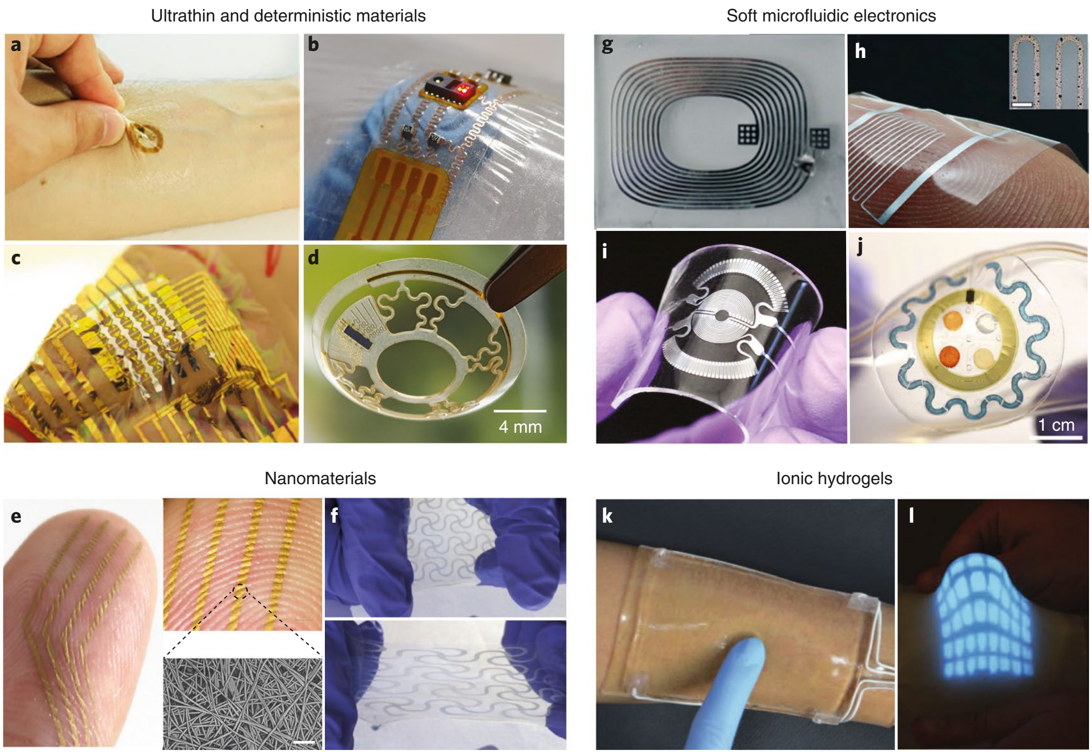

Fig. 4 | Advances in soft sensing, conductivity and artificial skin. a–d, Sensors fabricated from ultrathin and deterministic architectures. **e**,**f**, Conductive soft structures achieved by structured nanomaterials. Scale bar in **e**, 5 µm. **g**–**j**, Conductive and wearable devices enabled by 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 × 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 sweat[81].

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 stress[86]. These sensors are often well-suited for wearable devices and can be used to determine end-effector position and joint angles[87], or to translate the American Sign Language alphabet[88]. 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 activity[82] (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 LEDs[89]. Graphene sheets and graphene nanoscrolls are also effective for enabling conductivity in elastomers under high strain[92]. 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 flow[90].

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 deposition[96]. 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 encapsulation[96].

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-transparent[93] and contain field-effect transistors and other rigid, surface-mounted components[97] (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 sensors[98] or connect pre-packaged IC components[99]. EGaIn is particularly desirable for these applications because of its high conductivity, stable surface oxides, low toxicity and low viscosity[100].

The fabrication and filling of these liquid-metal microchannels has been a persistent challenge, with numerous techniques proposed in the literature, including injection[101], freeze placement[102] and direct writing[103]. Recent work has demonstrated fast and accurate filling of complex microchannel geometries via a vacuum[104] (Fig. 4g), as well as the fabrication of biphasic thin films by sputtering gold and thermally evaporating liquid gallium[105] (Fig. 4h). Several techniques have also focused on forming liquid-metal interconnects between IC devices[105].

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 sensing[83] or pressure sensing for tactile feedback and pulse monitoring[106] (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 devices[109]. As with the deterministic approach, some of these devices take explicit steps towards untethered functionality by incorporating NFC features to output sensor data wirelessly[83].

Beyond standard electronic components, soft microfluidics can be applied to wearable and untethered robotic devices in other ways as well. Perspiration pressure[110], rate[111] and composition[112] 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 limbs[12].

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 panels[113] (Fig. 4k), underwater DEAs[65], pulse and respiration sensors[114], and even stretchable electroluminescent displays and sensors[7] (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 sweat[112] and tune the dosage of drugs at controlled rates[115]. They can also incorporate rigid IC components and wavy interconnects, which allows hydrogel systems to blend electronic sensing with chemical activation[115]. 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 devices[116], 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), pneumatics[32] (Fig. 5f), and LCEs[35] (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

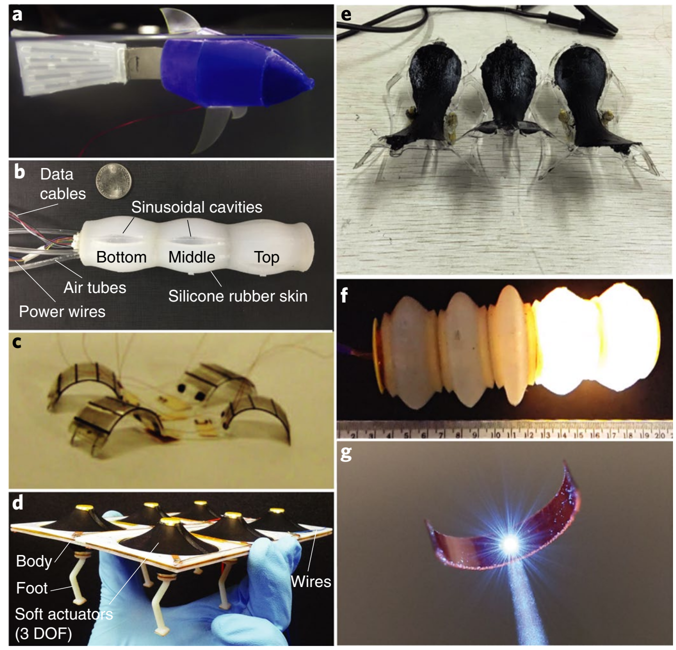

Fig. 5 | Implementation of soft actuators into robotic systems. a, SMA-actuated fish (20 cm long). **b**, SMA-actuated peristalsis robot (13.9 cm diameter). **c**, Fast DEA-actuated walker (6 cm). **d**, A multi-degree-of-freedom (DOF) DEA-powered walker. **e**, Differential friction, DEA-powered annelid 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 surfaces[118] (Fig. 6a), while Tolley et al. created a 0.65-m-long pneumatic robot capable of carrying batteries, compressors, valves and microprocessors[22] (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 efficiency[121]. 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 supply[65] (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 octopus[12] (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

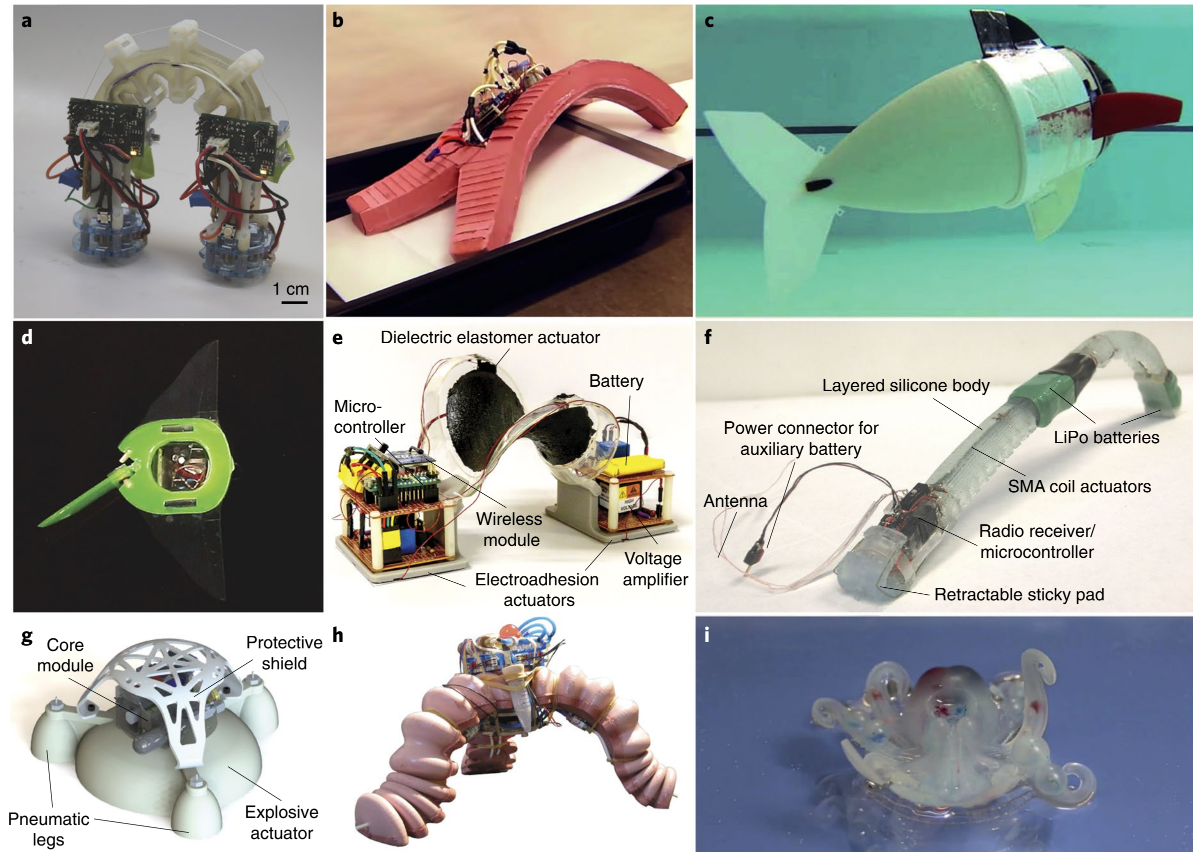

Fig. 6 | Fully untethered robotic systems. a, Climbing robot powered by a motor-cable system. **b**, Robust walking robot powered by on-board pneumatics (65 cm long). **c**, Biomimetic swimming robot powered by a hydraulic actuation system (35 cm long). **d**, Ray-inspired swimming robot powered by DEAs (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 environment[18]. 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 cell[81], incorporating flexible photovoltaics into a skin-conformal layer[126] or including thin stretchable triboelectric nanogenerators[127].

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 sensors[128], 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 printing[42], 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/layups. 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 state[58]. 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 demands[132]. 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 materials[55] 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 materials[135]) 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, multimaterial 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 multimaterial 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 biology[19] 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 actuator[138] 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.

Received: 17 October 2017; Accepted: 12 January 2018;
Published online: 8 February 2018

References

1. Majidi, C. Soft robotics: A perspective — current trends and prospects for the future. *Soft Robot.* **1**, 5–11 (2014).
2. Laschi, C., Mazzolai, B. & Cianchetti, M. Soft robotics: Technologies and systems pushing the boundaries of robot abilities. *Sci. Robot.* **1**, eaah3690 (2016).
3. Rus, D. & Tolley, M. T. Design, fabrication and control of soft robots. *Nature* **521**, 467–475 (2015).
4. Hammock, M. L., Chortos, A., Tee, B. C. K., Tok, J. B. H. & Bao, Z. 25th anniversary article: The evolution of electronic skin (E-Skin): A brief history, design considerations, and recent progress. *Adv. Mater.* **25**, 5997–6038 (2013).
5. Sfakiotakis, M., Kazakidi, A., Pateromichelakis, N. & Tsakiris, D. P. Octopus-inspired eight-arm robotic swimming by sculling movements. *Proc. IEEE Int. Conf. Robot. Autom.* 5155–5161 (2013).
6. Calisti, M., Corucci, F., Arienti, A. & Laschi, C. Dynamics of underwater legged locomotion: Modeling and experiments on an octopus-inspired robot. *Bioinspir. Biomim.* **10**, 046012 (2015).
7. Larson, C. et al. Highly stretchable electroluminescent skin for optical signaling and tactile sensing. *Science* **351**, 1071–1074 (2016).
8. Weigel, M. et al. iSkin. *Proc. 33rd Annu. ACM Conf. Hum. Factors Comput. Syst.* 2991–3000 (2015).
9. Jang, K. I. et al. Self-assembled three dimensional network designs for soft electronics. *Nat. Commun.* **8**, 15894 (2017).
10. O'Neill, C. T., Phipps, N. S., Cappello, L., Paganoni, S. & Walsh, C. J. A soft wearable robot for the shoulder: Design, characterization, and preliminary testing. *IEEE Int. Conf. Rehabil. Robot.* 1672–1678 (2017).
11. Li, Y. & Hashimoto, M. PVC gel soft actuator-based wearable assist wear for hip joint support during walking. *Smart Mater. Struct.* **26**, 125003 (2017).

12. Wehner, M. et al. An integrated design and fabrication strategy for entirely soft, autonomous robots. *Nature* **536**, 451–455 (2016).
13. Horchler, A. D. et al. Peristaltic locomotion of a modular mesh-based worm robot: Precision, compliance, and friction. *Soft Robot.* **2**, 135–145 (2015).
14. Jang, K. I. et al. Soft network composite materials with deterministic and bio-inspired designs. *Nat. Commun.* **6**, 1–11 (2015).
15. Kramer, R. K., Majidi, C. & Wood, R. J. Wearable tactile keypad with stretchable artificial skin. *Proc. IEEE Int. Conf. Robot. Autom.* 1103–1107 (2011).
16. Ilievski, F., Mazzeo, A. D., Shepherd, R. F., Chen, X. & Whitesides, G. M. Soft robotics for chemists. *Angew. Chem. Int. Ed.* **50**, 1890–1895 (2011).
17. Cvetkovic, C. et al. Three-dimensionally printed biological machines powered by skeletal muscle. *Proc. Natl Acad. Sci. USA* **111**, 10125–10130 (2014).
18. Nawroth, J. C. et al. A tissue-engineered jellyfish with biomimetic propulsion. *Nat. Biotechnol.* **30**, 792–797 (2012).
19. Khalil, A. S. & Collins, J. J. Synthetic biology: Applications come of age. *Nat. Rev. Genet.* **11**, 367–379 (2010).
20. Madden, J. D. W. et al. Artificial muscle technology: Physical principles and naval prospects. *IEEE J. Ocean. Eng.* **29**, 706–728 (2004).
21. Drotman, D., Jadhav, S., Karimi, M., Dezonia, P. & Tolley, M. T. 3D printed soft actuators for a legged robot capable of navigating unstructured terrain. *Proc. IEEE Int. Conf. Robot. Autom.* 5532–5538 (2017).
22. Tolley, M. T. et al. A resilient, untethered soft robot. *Soft Robot.* **1**, 213–223 (2014).
This work achieves untethered functionality by employing large pneumatic actuators and placing all standard auxiliary equipment on board.
23. Wall, V., Zoller, G. & Brock, O. A method for sensorizing soft actuators and its application to the RBO hand 2. *Proc. IEEE Int. Conf. Robot. Autom.* 4965–4970 (2017).
24. Raitor, M., Walker, J. M., Okamura, A. M. & Culbertson, H. WRAP: Wearable, restricted-aperture pneumatics for haptic guidance. *Proc. IEEE Int. Conf. Robot. Autom.* 427–432 (2017).
25. Wirekoh, J. & Park, Y.-L. Design of flat pneumatic artificial muscles. *Smart Mater. Struct.* **26**, 035009 (2017).
26. Fras, J., Noh, Y., Wurdemann, H. & Althoefer, K. Soft fluidic rotary actuator with improved actuation properties. *2017 IEEE/RSJ Int. Conf. Intell. Robot. Syst.* 5610–5615 (2017).
27. Yan, J., Xu, B., Zhang, X. & Zhao, J. Design and test of a new spiral driven pure torsional soft actuator. In *Intelligent Robotics and Applications: 10th Int. Conf., ICIRA 2017*, Part 1 (eds Huang, Y. et al.) **10462**, 127–139 (Springer, 2017).
28. Yang, D. et al. Buckling pneumatic linear actuators inspired by muscle. *Adv. Mater. Technol.* **1**, 1600055 (2016).
29. Licht, S., Collins, E., Mendes, M. L. & Baxter, C. Stronger at depth: Jamming grippers as deep sea sampling tools. *Soft Robot.* **4**, 305–316 (2017).
30. Miriyev, A., Stack, K. & Lipson, H. Soft material for soft actuators. *Nat. Commun.* **8**, 1–8 (2017).
31. Tolley, M. T. et al. An untethered jumping soft robot. *IEEE Int. Conf. Intell. Robot. Syst.* 561–566 (2014).
32. Nemitz, M. P., Mihaylov, P., Barraclough, T. W., Ross, D. & Stokes, A. A. Using voice coils to actuate modular soft robots: Wormbot, an example. *Soft Robot.* **3**, 198–204 (2016).
33. Zeng, H., Wani, O. M., Wasylczyk, P., Kaczmarek, R. & Priimagi, A. Self-regulating iris based on light-actuated liquid crystal elastomer. *Adv. Mater.* **29**, 1–7 (2017).
34. Baytekin, B., Cezan, S. D., Baytekin, H. T. & Grzybowski, B. A. Artificial heliotropism and nyctinasty based on optomechanical feedback and no electronics. *Soft Robot.* https://doi.org/10.1089/soro.2017.0020 (2017).
This work demonstrates untethered environmental responsiveness (that is, sun tracking) without employing the need for batteries by directly heating shape-memory alloys with sunlight.
35. Wani, O. M., Zeng, H. & Priimagi, A. A light-driven artificial flytrap. *Nat. Commun.* **8**, 15546 (2017).
36. Zeng, H., Wani, O. M., Wasylczyk, P. & Priimagi, A. Light-driven, caterpillar-inspired miniature inching robot. *Macromol. Rapid Commun.* **39**, 1700224 (2017).
37. Palagi, S. et al. Structured light enables biomimetic swimming and versatile locomotion of photoresponsive soft microrobots. *Nat. Mater.* **15**, 647–653 (2016).
38. Rogóż, M., Zeng, H., Xuan, C., Wiersma, D. S. & Wasylczyk, P. Light-driven soft robot mimics caterpillar locomotion in natural scale. *Adv. Opt. Mater.* **4**, 1689–1694 (2016).
39. Francis, W., Dunne, A., Delaney, C., Florea, L. & Diamond, D. Spiropyran based hydrogels actuators — Walking in the light. *Sens. Actuat. B* **250**, 608–616 (2017).
40. Amjadi, M. & Sitti, M. High-performance multiresponsive paper actuators. *ACS Nano* **10**, 10202–10210 (2016).
41. Loepfe, M., Schumacher, C. M., Lustenberger, U. B. & Stark, W. J. An untethered, jumping roly-poly soft robot driven by combustion. *Soft Robot.* **2**, 33–41 (2015).
42. Bartlett, N. W. et al. A 3D-printed, functionally graded soft robot powered by combustion. *Science* **349**, 161–165 (2015).
43. Patino, T., Mestre, R. & Sánchez, S. Miniaturized soft bio-hybrid robotics: a step forward into healthcare applications. *Lab Chip* **16**, 3626–3630 (2016).
44. Feinberg, A. W. et al. Muscular thin films for building actuators and powering devices. *Science* **317**, 1366–1370 (2007).
45. Raman, R. et al. Optogenetic skeletal muscle-powered adaptive biological machines. *Proc. Natl Acad. Sci. USA* **113**, 3497–3502 (2016).
46. Park, S. J. et al. Phototactic guidance of a tissue-engineered soft-robotic ray. *Science* **353**, 158–162 (2016).
This work demonstrates untethered control of bio-hybrid robots using light.
47. Yoon, J., Eyster, T. W., Misra, A. C. & Lahann, J. Cardiomyocyte-driven actuation in biohybrid microcylinders. *Adv. Mater.* **27**, 4509–4515 (2015).
48. Holley, M. T., Nagarajan, N., Danielson, C., Zorlutuna, P. & Park, K. Development and characterization of muscle-based actuators for self-stabilizing swimming biorobots. *Lab Chip* **16**, 3473–3484 (2016).
49. Kang, H. W. et al. A 3D bioprinting system to produce human-scale tissue constructs with structural integrity. *Nat. Biotechnol.* **34**, 312–319 (2016).
50. Wehner, M. et al. Pneumatic energy sources for autonomous and wearable soft robotics. *Soft Robot.* **1**, 263–274 (2014).
51. Kim, S. et al. Micro artificial muscle fiber using NiTi spring for soft robotics. *2009 IEEE/RSJ Int. Conf. Intell. Robot. Syst.* 2228–2234 (2009).
52. Jin, H. et al. Soft and smart modular structures actuated by shape memory alloy (SMA) wires as tentacles of soft robots. *Smart Mater. Struct.* **25**, 085026 (2016).
53. Cheng, S. S., Kim, Y. & Desai, J. P. New actuation mechanism for actively cooled SMA springs in a neurosurgical robot. *IEEE Trans. Robot.* **33**, 986–993 (2017).
54. Alcaide, J. O., Pearson, L. & Rentschler, M. E. Design, modeling and control of a SMA-actuated biomimetic robot with novel functional skin. *Proc. IEEE Int. Conf. Robot. Autom.* 4338–4345 (2017).
55. Bartlett, M. D. et al. High thermal conductivity in soft elastomers with elongated liquid metal inclusions. *Proc. Natl Acad. Sci. USA* **114**, 2143–2148 (2017).
56. Rodrigue, H., Wang, W., Kim, D. R. & Ahn, S. H. Curved shape memory alloy-based soft actuators and application to soft gripper. *Compos. Struct.* **176**, 398–406 (2017).
57. Song, S. H. et al. Turtle mimetic soft robot with two swimming gaits. *Bioinspir. Biomim.* **11**, 036010 (2016).
58. Rich, S., Jang, S.-H., Park, Y.-L. & Majidi, C. Liquid metal-conductive thermoplastic elastomer integration for low-voltage stiffness tuning. *Adv. Mater. Technol.* **2**, 1700179 (2017).
59. Yuan, C. et al. 3D printed reversible shape changing soft actuators assisted by liquid crystal elastomers. *Soft Matter* **13**, 5558–5568 (2017).
60. Horiuchi, T., Mihashi, T., Fujikado, T., Oshika, T. & Asaka, K. Voltage-controlled IPMC actuators for accommodating intra-ocular lens systems. *Smart Mater. Struct.* **26**, 045021 (2017).
61. Carrico, J. D., Kim, K. J. & Leang, K. K. 3D-printed ionic polymer-metal composite soft crawling robot. *Proc. IEEE Int. Conf. Robot. Autom.* 4313–4320 (2017).
62. Yang, T. & Chen, Z. Development of 2D maneuverable robotic fish propelled by multiple ionic polymer–metal composite artificial fins. *2015 IEEE Int. Conf. Robot. Biomimetics, IEEE-ROBIO 2015* **1**, 255–260 (2015).
63. Duduta, M., Clarke, D. R. & Wood, R. J. A high speed soft robot based on dielectric elastomer actuators. *2017 IEEE Int. Conf. Robot. Autom.* 4346–4351 (2017).
64. Godaba, H., Li, J., Wang, Y. & Zhu, J. A soft jellyfish robot driven by a dielectric elastomer actuator. *IEEE Robot. Autom. Lett.* **1**, 624–631 (2016).
65. Li, T. et al. Fast-moving soft electronic fish. *Sci. Adv.* **3**, e1602045 (2017).
This work demonstrates a fast untethered underwater robot with a long battery life, based on low-power dielectric elastomer actuators.
66. Sun, W., Liu, F., Ma, Z., Li, C. & Zhou, J. Soft mobile robots driven by foldable dielectric elastomer actuators. *J. Appl. Phys.* **120**, 084901 (2016).
67. Henke, E.-F. M., Wilson, K. E. & Anderson, I. A. Entirely soft dielectric elastomer robots. *Proc. SPIE* **10163**, 101631N (2017).
68. Nguyen, C. T., Phung, H., Nguyen, T. D., Jung, H. & Choi, H. R. Multiple-degrees-of-freedom dielectric elastomer actuators for soft printable hexapod robot. *Sens. Actuat. A* **267**, 505–516 (2017).
69. Shintake, J., Schubert, B., Rosset, S., Shea, H. & Floreano, D. Variable stiffness actuator for soft robotics using dielectric elastomer and low-melting-point alloy. *IEEE Int. Conf. Intell. Robot. Syst.* 1097–1102 (2015).

70. Shintake, J., Rosset, S., Schubert, B., Floreano, D. & Shea, H. Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators. *Adv. Mater.* **28**, 231–238 (2016).
71. Kazem, N., Hellebrekers, T. & Majidi, C. Soft multifunctional composites and emulsions with liquid metals. *Adv. Mater.* **29**, 1–14 (2017).
72. Khang, D.-Y., Jiang, H., Huang, Y. & Rogers, J. A. A stretchable form of single-crystal. *Science* **311**, 208–212 (2006).
73. Liu, Y. et al. Epidermal mechano-acoustic sensing electronics for cardiovascular diagnostics and human-machine interfaces. *Sci. Adv.* **2**, e1601185 (2016).
74. Kim, J. et al. Battery-free, stretchable optoelectronic systems for wireless optical characterization of the skin. *Sci. Adv.* **2**, e1600418 (2016). **This work shows battery-free biological sensing that can wirelessly deliver data to an NFC-enabled device.**
75. Bartlett, M. D., Markvicka, E. J. & Majidi, C. Rapid fabrication of soft, multilayered electronics for wearable biomonitoring. *Adv. Funct. Mater.* **26**, 8496–8504 (2016).
76. Kaltenbrunner, M. et al. An ultra-lightweight design for imperceptible plastic electronics. *Nature* **499**, 458–463 (2013).
77. Yokota, T. et al. Ultraflexible organic photonic skin. *Sci. Adv.* **2**, e1501856 (2016).
78. Lee, W. et al. Integration of organic electrochemical and field-effect transistors for ultraflexible, high temporal resolution electrophysiology arrays. *Adv. Mater.* **28**, 9722–9728 (2016).
79. Plovie, B. et al. Arbitrarily shaped 2.5D circuits using stretchable interconnects embedded in thermoplastic polymers. *Adv. Eng. Mater.* **19**, 1–8 (2017).
80. Vásquez Quintero, A., Verplancke, R., De Smet, H. & Vanfleteren, J. Stretchable electronic platform for soft and smart contact lens applications. *Adv. Mater. Technol.* **2**, 1700073 (2017).
81. Bandodkar, A. J. et al. Soft, stretchable, high power density electronic skin-based biofuel cells for scavenging energy from human sweat. *Energy Environ. Sci.* **10**, 1581–1589 (2017).
82. Miyamoto, A. et al. Inflammation-free, gas-permeable, lightweight, stretchable on-skin electronics with nanomeshes. *Nat. Nanotech.* **12**, 907–913 (2017).
83. Varga, M., Ladd, C., Ma, S., Holbery, J. & Tröster, G. On-skin liquid metal inertial sensor. *Lab Chip* **17**, 3272–3278 (2017).
84. Xu, T. et al. Three-dimensional and ultralight sponges with tunable conductivity assembled from electrospun nanofibers for highly sensitive tactile pressure sensor. *J. Mater. Chem. C* **5**, 10288–10294 (2017).
85. Luo, W., Wu, T., Chen, B., Liang, M. & Zou, H. Highly stretchable conductors based on expanded graphite macro-confined in tubular rubber. *ACS Appl. Mater. Inter.* **9**, 43239–43249 (2017).
86. Segev-Bar, M., Konvalina, G. & Haick, H. High-resolution unpixelated smart patches with antiparallel thickness gradients of nanoparticles. *Adv. Mater.* **27**, 1779–1784 (2015).
87. Yuen, M. C., Tonoyan, H., White, E. L., Telleria, M. & Kramer, R. K. Fabric sensory sleeves for soft robot state estimation. *Proc. IEEE Int. Conf. Robot. Autom.* 5511–5518 (2017).
88. O'Connor, T. F. et al. The language of glove: Wireless gesture decoder with low-power and stretchable hybrid electronics. *PLoS One* **12**, e0179766 (2017).
89. You, B., Kim, Y., Ju, B. K. & Kim, J. W. Highly stretchable and waterproof electroluminescence device based on superstable stretchable transparent electrode. *ACS Appl. Mater. Inter.* **9**, 5486–5494 (2017).
90. Shuai, X. et al. Highly sensitive flexible pressure sensor based on silver nanowires-embedded polydimethylsiloxane electrode with microarray structure. *ACS Appl. Mater. Inter.* **9**, 26314–26324 (2017).
91. Ma, L., Shuai, X., Zhu, P. & Sun, R. A highly sensitive flexible pressure sensor based on multi-scale structure and silver nanowires. *2017 Int. Conf. Electron. Packag. Technol.* 1366–1370 (2017).
92. Liu, N. et al. Ultratransparent and stretchable graphene electrodes. *Sci. Adv.* **3**, e1700159 (2017).
93. Pyo, S., Choi, J. & Kim, J. Flexible, transparent, sensitive, and crosstalk-free capacitive tactile sensor array based on graphene electrodes and air dielectric. *Adv. Electron. Mater.* **4**, 1700427 (2017).
94. White, E. L., Yuen, M. C., Case, J. C. & Kramer, R. K. Low-cost, facile, and scalable manufacturing of capacitive sensors for soft systems. *Adv. Mater. Technol.* **2**, 1700072 (2017).
95. Muth, J. T. et al. Embedded 3D printing of strain sensors within highly stretchable elastomers. *Adv. Mater.* **26**, 6307–6312 (2014).
96. Sencadas, V., Mutlu, R. & Alici, G. Large area and ultra-thin compliant strain sensors for prosthetic devices. *Sens. Actuat. A* **266**, 56–64 (2017).
97. Wang, Y. et al. A highly stretchable, transparent, and conductive polymer. *Sci. Adv.* **3**, e1602076 (2017).
98. Majidi, C., Park, Y. L., Kramer, R., Brard, P. & Wood, R. J. Hyperelastic pressure sensing with a liquid-embedded elastomer. *J. Micromech. Microeng.* **20**, 125029 (2010).
99. Zhang, B., Dong, Q., Korman, C. E., Li, Z. & Zaghloul, M. E. Flexible packaging of solid-state integrated circuit chips with elastomeric microfluidics. *Sci. Rep.* **3**, 1098 (2013).
100. Dickey, M. D. Emerging applications of liquid metals featuring surface oxides. *ACS Appl. Mater. Inter.* **6**, 18369–18379 (2014).
101. Dickey, M. D. et al. Eutectic gallium-indium (EGaIn): A liquid metal alloy for the formation of stable structures in microchannels at room temperature. *Adv. Funct. Mater.* **18**, 1097–1104 (2008).
102. Fassler, A. & Majidi, C. 3D structures of liquid-phase GaIn alloy embedded in PDMS with freeze casting. *Lab Chip* **13**, 4442–4450 (2013).
103. Boley, J. W., White, E. L., Chiu, G. T. C. & Kramer, R. K. Direct writing of gallium-indium alloy for stretchable electronics. *Adv. Funct. Mater.* **24**, 3501–3507 (2014).
104. Lin, Y. et al. Vacuum filling of complex microchannels with liquid metal. *Lab Chip* **17**, 3043–3050 (2017).
105. Hirsch, A., Michaud, H. O., Gerratt, A. P., de Mulatier, S. & Lacour, S. P. Intrinsically stretchable biphasic (solid–liquid) thin metal films. *Adv. Mater.* **28**, 4507–4512 (2016).
106. Gao, Y. et al. Wearable microfluidic diaphragm pressure sensor for health and tactile touch monitoring. *Adv. Mater.* **29**, 1701985 (2017).
107. Tiziani, L. O., Cahoon, T. W. & Hammond, F. L. Sensorized pneumatic muscle for force and stiffness control. *2017 IEEE Int. Conf. Robot. Autom.* 5545–5552 (2017).
108. King, J. P., Valle, L. E., Pol, N. & Park, Y.-L. Design, modeling, and control of pneumatic artificial muscles with integrated soft sensing. *2017 IEEE Int. Conf. Robot. Autom.* 4985–4990 (2017).
109. Moon, Y. G. et al. Freely deformable liquid metal grids as stretchable and transparent electrodes. *IEEE T. Electron. Dev.* 1–6 (2017).
110. Choi, J. et al. Soft, skin-mounted microfluidic systems for measuring secretory fluidic pressures generated at the surface of the skin by eccrine sweat glands. *Lab Chip* **17**, 2572–2580 (2017).
111. Choi, J., Kang, D., Han, S., Kim, S. B. & Rogers, J. A. Thin, soft, skin-mounted microfluidic networks with capillary bursting valves for chrono-sampling of sweat. *Adv. Healthc. Mater.* **6**, 1–10 (2017).
112. Koh, A. et al. A soft, wearable microfluidic device for the capture, storage, and colorimetric sensing of sweat. *Sci. Transl. Med.* **8**, 366ra165 (2016). **This work shows a method for electronics-free chemical sensing (that is, sweat analysis) by employing microfluidic channels and enzymatic reactions.**
113. Kim, C. C., Lee, H. H., Oh, K. H. & Sun, J. Y. Highly stretchable, transparent ionic touch panel. *Science* **353**, 682–687 (2016).
114. Darabi, M. A. et al. Skin-inspired multifunctional autonomic-intrinsic conductive self-healing hydrogels with pressure sensitivity, stretchability, and 3D printability. *Adv. Mater.* **29**, 1–8 (2017).
115. Lin, S. et al. Stretchable hydrogel electronics and devices. *Adv. Mater.* **28**, 4497–4505 (2016).
116. Wirthl, D. et al. Instant tough bonding of hydrogels for soft machines and electronics. *Sci. Adv.* **3**, e1700053 (2017).
117. Xu, L. et al. Bio-inspired annelid robot: A dielectric elastomer actuated soft robot. *Bioinspir. Biomim.* **12**, 025003 (2017).
118. Malley, M., Rubenstein, M. & Nagpal, R. Flippy: A soft, autonomous climber with simple sensing and control. *2017 IEEE/RSJ Int. Conf. Intell. Robot. Syst.* https://doi.org/10.1109/IROS.2017.8206563 (2017).
119. Marchese, A. D., Katzschmann, R. K. & Rus, D. A recipe for soft fluidic elastomer robots. *Soft Robot.* **2**, 7–25 (2015).
120. Marchese, A. D., Onal, C. D. & Rus, D. Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators. *Soft Robot.* **1**, 75–87 (2014).
121. Shui, L., Zhu, L., Yang, Z., Liu, Y. & Chen, X. Energy efficiency of mobile soft robots. *Soft Matter* **13**, 8223–8233 (2017).
122. Lin, H. T., Leisk, G. G. & Trimmer, B. GoQBot: A caterpillar-inspired soft-bodied rolling robot. *Bioinspir. Biomim.* **6**, 026007 (2011).
123. Cao, J., Qin, L., Lee, H. P. & Zhu, J. Development of a soft untethered robot using artificial muscle actuators. *Proc. SPIE* **10163**, 101631X (2017).
124. Bartlett, N. W. et al. Robot powered by combustion. *Science* **349**, 161–165 (2015).
125. Zamarayeva, A. M. et al. Flexible and stretchable power sources for wearable electronics. *Sci. Adv.* **3**, e1602051 (2017). **This work provides a potential power source for soft, untethered systems by demonstrating a stretchable battery.**
126. O'Connor, T. F. et al. Wearable organic solar cells with high cyclic bending stability: Materials selection criteria. *Sol. Energy Mater. Sol. Cells* **144**, 438–444 (2016).
127. Chen, X. et al. On-skin triboelectric nanogenerator and self-powered sensor with ultrathin thickness and high stretchability. *Small* **13**, 1702929 (2017). This work demonstrates a tactile sensing system that is powered by an on-board nano-generator, requiring neither battery nor power cable.

128. Yang, H., Chen, Y., Sun, Y. & Hao, L. A novel pneumatic soft sensor for measuring contact force and curvature of a soft gripper. *Sens. Actuat. A* **266**, 318–327 (2017).
129. Naserifar, N., LeDuc, P. R. & Fedder, G. K. Drop casting of stiffness gradients for chip integration into stretchable substrates. *J. Micromech. Microeng.* **27**, 045018 (2017).
130. Naserifar, N., LeDuc, P. R. & Fedder, G. K. Material gradients in stretchable substrates toward integrated electronic functionality. *Adv. Mater.* **28**, 3584–3591 (2016).
131. Park, C. W. et al. Photolithography-based patterning of liquid metal interconnects for monolithically integrated stretchable circuits. *ACS Appl. Mater. Inter.* **8**, 15459–15465 (2016).
132. Mariangela, M., Cacucciolo, V. & Cianchetti, M. Stiffening in soft robotics: A review of the state of the art. *IEEE Robot. Autom. Mag.* **23**, 93–106 (2016).
133. Yang, W. et al. On the tear resistance of skin. *Nat. Commun.* **6**, 6649 (2015).
134. Terryn, S., Brancart, J., Lefeber, D., Van Assche, G. & Vanderborght, B. Self-healing soft pneumatic robots. *Sci. Robot.* **2**, eaan4268 (2017).
135. Walker, S. et al. Using an environmentally benign and degradable elastomer in soft robotics. *Int. J. Intell. Robot. Appl.* **1**, 124–142 (2017).
136. McEvoy, M. A. & Correll, N. Materials that couple sensing, actuation, computation, and communication. *Science* **347**, 1261689 (2015).
137. Pfeifer, R. & Gomez, G. Morphological computation — Connecting brain, body, and environment. In *Creating Brain-Like Intelligence* (eds Sendhoff, B., Körner, E., Sporns, O., Ritter, H. & Doya, K.) 66–83 (Springer, 2009).
138. Brown, E. et al From the cover: Universal robotic gripper based on the jamming of granular material. *Proc. Natl Acad. Sci. USA* **107**, 8809–18814 (2010).
139. Rogers, J. A. Wearable electronics: Nanomesh on-skin electronics. *Nat. Nanotech.* **12**, 839–840 (2017).

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
Reprints and permissions information is available at www.nature.com/reprints.

Correspondence and requests for materials should be addressed to C.M.

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.