# Soft robotics: a bioinspired evolution in robotics

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**Animals exploit soft structures to move effectively in complex natural environments. These capabilities have inspired robotic engineers to incorporate soft technologies into their designs. The goal is to endow robots with new, bioinspired capabilities that permit adaptive, flexible interactions with unpredictable environments. Here, we review emerging soft-bodied robotic systems, and in particular recent developments inspired by soft-bodied animals. Incorporating soft technologies can potentially reduce the mechanical and algorithmic complexity involved in robot design. Incorporating soft technologies will also expedite the evolution of robots that can safely interact with humans and natural environments. Finally, soft robotics technology can be combined with tissue engineering to create hybrid systems for medical applications.**

## Soft biological materials inspire a new wave of robotics

Human-made manufacturing robots are mostly designed to be stiff so that they can perform fast, precise, strong, and repetitive position control tasks in assembly lines. Common actuators in such robotic systems are composed of rigid electromagnetic components (e.g., magnets, copper, and steel bearings) or internal combustion engines made of steel and aluminum alloys. By contrast, in the animal world soft materials prevail. The vast majority of animals are soft bodied, and even animals with stiff exoskeletons such as insects have long-lived life stages wherein they are almost entirely soft (maggots, grubs, and caterpillars). Even animals with stiff endoskeletons are mainly composed of soft tissues and liquids. For example, the human skeleton typically contributes only 11% of the body mass of an adult male, whereas skeletal muscle contributes an average 42% of body mass. In addition, parts of animal bodies that play supportive roles in locomotion (e.g., digestion, gas and heat exchange, and motor control) are highly deformable as well.

Studying how animals use soft materials to move in complex, unpredictable environments can provide invaluable insights for emerging robotic applications in medicine, search and rescue, disaster response, and human assistance. All these situations require robots to handle unexpected interactions with unstructured environments or humans. Soft robotics aims to equip robots for the unpredictable needs of such situations by endowing them with capabilities that are based not in control systems but in the material properties and morphology of their bodies (Figure 1) [1]. Soft robotics is a growing, new field that focuses on these mechanical qualities and on the integration of materials, structures, and software. In the same way that animal movements are based on the tight integration of neural and mechanical controls, soft robotics aims to achieve better and simpler mechanisms by exploiting the 'mechanical intelligence' of soft materials.

In this article we introduce robotic systems that are fundamentally soft and highly deformable [2]. These robots are differentiated from other approaches in which the machines are built using hard materials and compliance is achieved using variable- stiffness actuators and compliant control [3]. We discuss the key biomechanical features of three soft animals that are used as inspiration for different soft robotic systems and suggest future directions where soft robotics can be integrated with tissue engineering for medical applications.

### *Lessons from biology*

Soft materials are essential to the mechanical design of animals, and their body structures have coevolved with the central nervous system to form a completely integrated neuromechanical control system. These soft components provide numerous advantages, helping animals negotiate and adapt to changing, complex environments. They conform to surfaces, distribute stress over a larger volume, and increase contact time, thereby lowering the maximum impact force. Soft materials also lend themselves to highly flexible and deformable structures, providing additional functional advantages to animals, such as enabling entrance into small apertures for shelter or hunting. Simple examples include the soft paws of mammalian runners that damp the force of impact when their legs strike the ground, and the soft finger pads and skin of arboreal animals that assist climbing by conforming to surfaces for better grip or adhesion.

Ultimately it is probably the ecological niche that determines the evolutionary tendency to be stiff or soft. Animals that do not need to travel quickly or exert high-impact forces do not need a permanently stiff skeleton and can instead develop highly deformable bodies that allow them to exploit behaviors and environments unavailable to

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*Keywords:* bio-inspired robot; soft robotics.

0167-7799/$ – see front matter
 http://dx.doi.org/10.1016/j.tibtech.2013.03.002

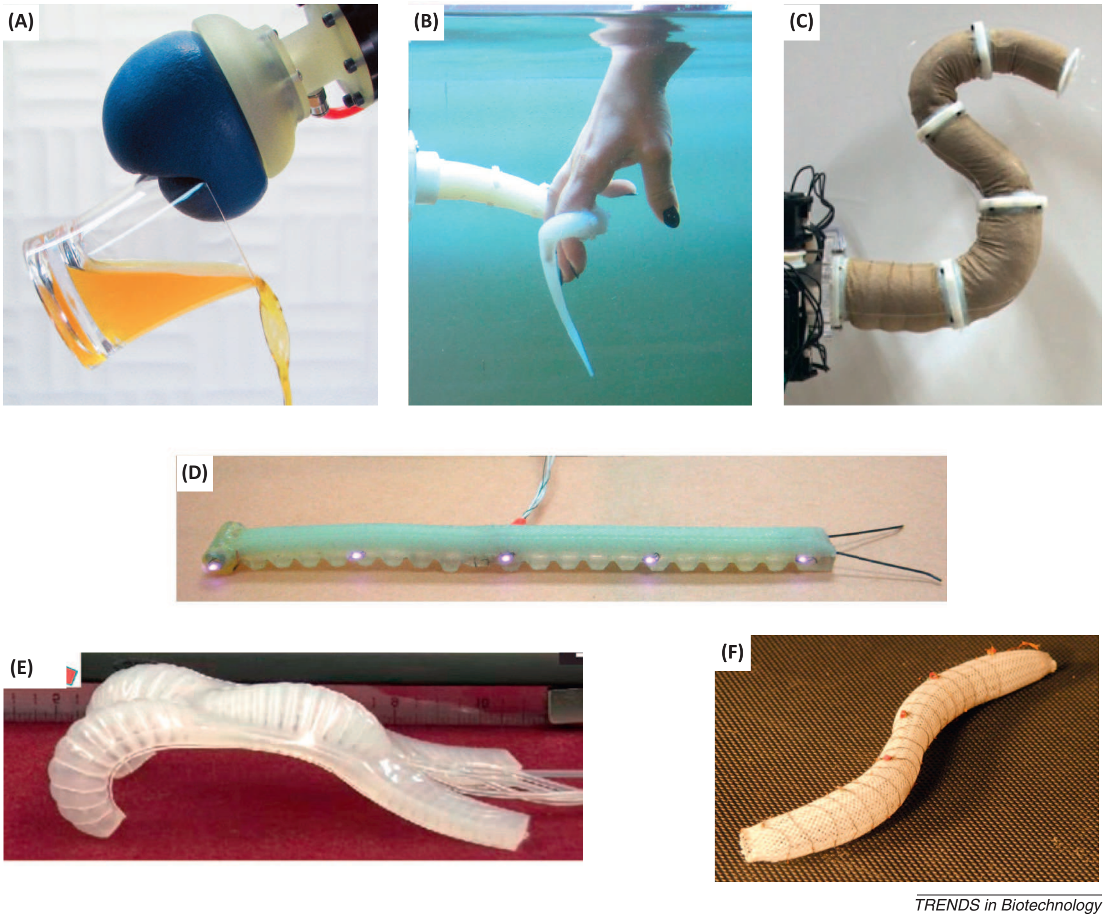


**Figure 1**. Recent development of robots that incorporate soft materials. **(A)** A soft gripper composed of a flexible sac filled with granular materials that can grasp a wide range of objects by vacuum pressure control [56]. **(B)** A soft manipulator modeled on the characteristic muscle structure of the octopus [7]. **(C)** The GoQBot, capable of the ballistic rolling motion observed in caterpillars [8]. **(D)** A multigait soft walker powered by compressed air [39]. **(E)** The Meshworm, which attains peristaltic locomotion by contracting its body, made of compliance mesh [6].

skeletal animals. The octopus can mimic its surroundings, caterpillars can conform to their host plants to be cryptic, and all of them can squeeze through gaps smaller than their unconstrained body. These are important lessons for building soft robots.

For all of their advantages, soft biological structures have some important limitations. Soft animals tend to be small because it is difficult for them to support their own body weight without a skeleton. All of the extremely large soft invertebrates are found either in water (squid and jellyfish) or underground (giant earthworms), where their body is supported by the surrounding medium. Similar limitations would apply to soft robots and necessitate careful selection of materials to match size as well as function. Additionally, the high deformability and energy-absorbing properties of soft tissues prevent them from exerting large inertial forces and limit how fast soft animals can move from place to place. This does not prevent different parts of the body from moving quickly under low loads. Octopuses can extend their limbs quickly by exploiting the fixed volume, low-aspect ratio geometry of their arms [4], and carnivorous caterpillars can strike their prey within a few hundred milliseconds [5]. However, these considerations make it likely that terrestrial soft robots bigger than a mouse or rat will incorporate stiff components for better performance, taking advantage of high flexibility.

## Soft-bodied animals and soft-bodied robots

One problem with developing robots that use soft materials is that we currently have no general theory of how to control such unconstrained structures. Robotics engineers have begun to develop this knowledge by building robot models based on the neuromechanical strategies that soft-bodied animals use to locomote, chiefly annelids (earthworms and leeches)[6], molluscs (primarily the octopus)[7], and insect larvae (caterpillars) [8].

### *Worms and worm-like robots*

From a biomechanical perspective, worms are fixed-volume hydrostats. They mimic the mechanical actions of a lever by transforming force and displacement through Pascal's principle. Contraction of longitudinal muscles shortens the body and increases its diameter, whereas contraction of circumferential muscles decreases the diameter and elongates the body [9,10] (Figure 2). Worms achieve locomotion by creating traveling waves of contraction and expansion using their cylindrical segments, a process that is analogous to intestinal peristalsis. The directions of the locomotion and the traveling wave can be the same or opposite, depending on the timing of contact with the terrain [11].

Many worm-like robots have been developed based on hydrostatic structures, with a range of hard and soft

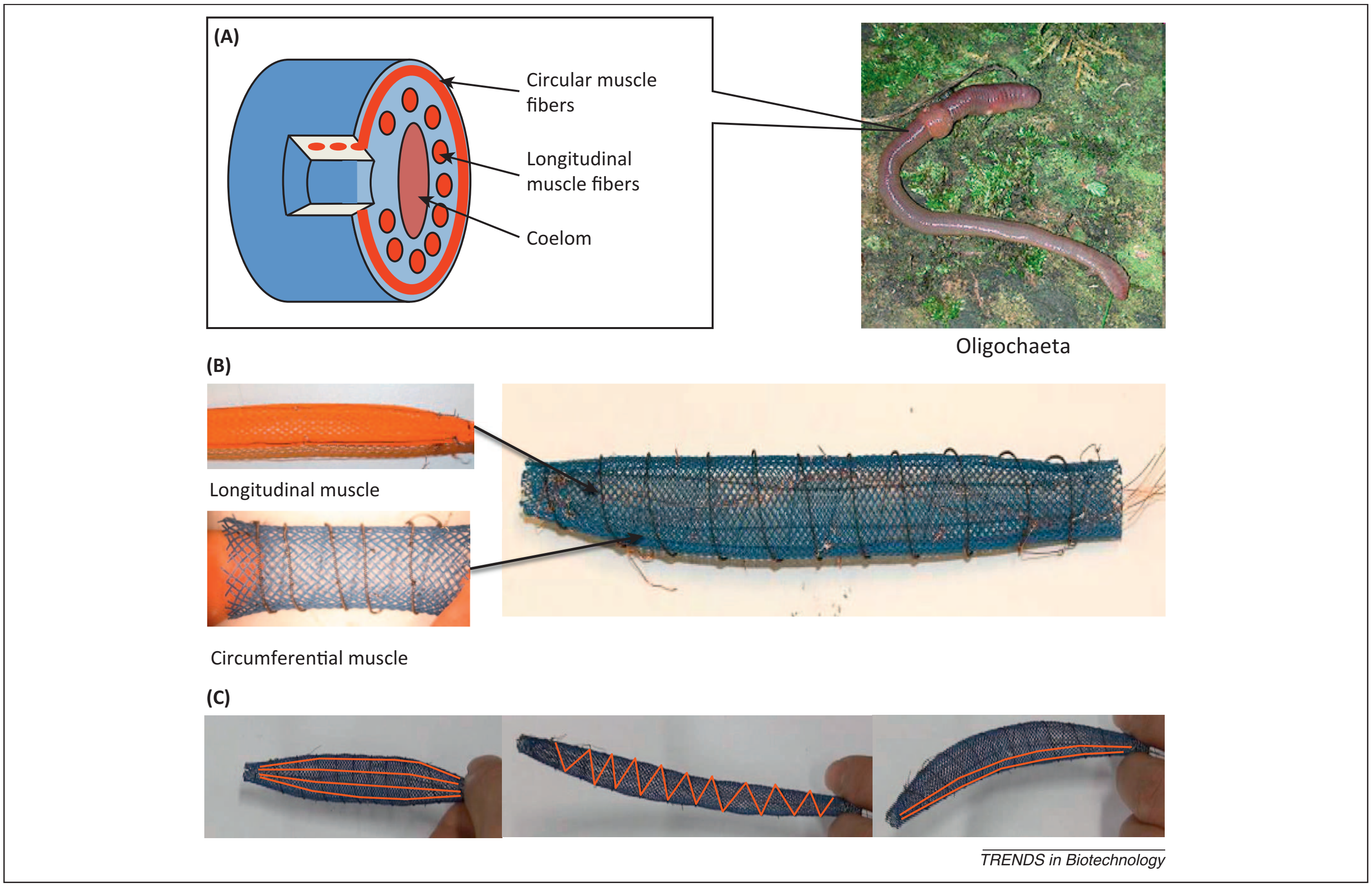


**Figure 2.** Earth worm-inspired robot. **(A)** Muscular structure of Oligochaeta, which forms antagonistic pairs without skeleton or joint. **(B)** A mesh structure that contains longitudinal and circumferential artificial muscles, creating an antagonistic pairing similar to the pairing in Oligochaeta. **(C)** Demonstration of various actuation modes.

actuators. One example uses pressure actuators with air valves, metal springs, and thermoplastic bearings [12], and an annelid robot uses a stack of dielectric elastomers mounted on a printed circuit board inside a silicone skin to generate worm-like movement [13]. Many worm-like robots have used shape–memory alloy (SMA) actuators, pioneered in the worm-like crawler [14] and later in a jointed, segmented worm robot that mimics how nematodes swim [15]. The Meshworm is the most recent device to use the SMA technology (Figure 1E) [6]. The Meshworm is based on a constant-length design rather than the constant-volume design that worms use. Radial SMA contraction in one segment causes radial expansion of an adjacent segment, and propulsion is derived from peristaltic waves of ground contacts. Linear potentiometers that detect the length of each segment provide feedback. Using iterative learning, the duration of each SMA actuation is adjusted to maximize either the speed of the Meshworm or its traveling distance and energy consumption. Steering is achieved by replacing two of the passive tendons with longitudinal SMA coils. Activation of one coil shortens one side of the robot and biases its movements in that direction. This robot demonstrates a key feature of soft technology: it can be hit repeatedly with a hammer and still function reliably.

### *Caterpillars and caterpillar-like robots*

Although sometimes confused with worms, the larval stages of insects have a completely different anatomy and locomotion strategy. Burrowing species such as fly larvae (maggots) and sedentary *Hymenoptera* larvae (e.g., wasps) generally lack limbs, but butterfly and moth larvae are highly active climbing animals with well-developed gripping appendages called prolegs. Although their bodies appear to be segmented, there are no internal divisions between these segments, just a single continuous body cavity called the hemocele. Caterpillar musculature is surprisingly complex, with as many as 2000 motor units distributed throughout. There are no circumferential muscles, only longitudinal muscles, oblique muscles, and many small muscles attached to the limbs and other body parts (Figure 3A). Caterpillars can adjust pressure to increase body stiffness so that they can cantilever their body across a gap, but they do not appear to use pressure as a major control variable for most other movements [16–18].

Caterpillars crawl and climb by exerting compressive forces on the substrate (the so-called ‘environmental skeleton hypothesis’) [19,20] and controlling the release of body tension. Waves of muscular contraction do not appear to be tightly coordinated [21,22] but serve primarily to redistribute mechanical energy stored in elastic tissues [23]. The coordination of movement is determined by controlling the timing and location of substrate attachment by means of hooks at the tip of the prolegs [24,25]. The hooks grip in a purely passive way, but release is actively accomplished by a single pair of retractor muscles controlled by three motoneurons [26,27]. This is remarkable because a single proleg can produce sufficient grip to prevent any forward

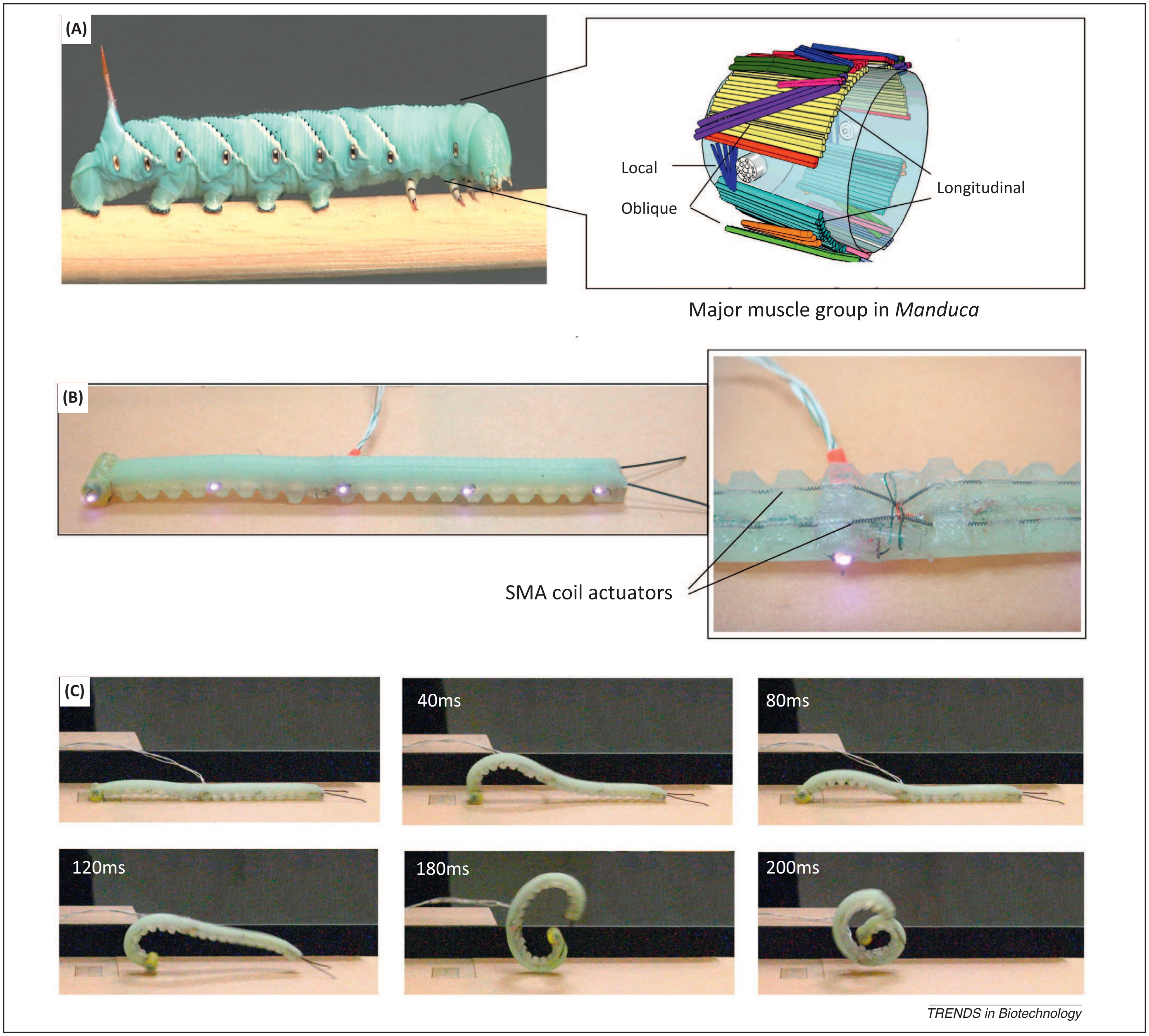


**Figure 3**. Caterpillar-inspired robot. **(A)** The caterpillar as a model organism for studying the control of soft-bodied movements (tobacco hornworm *Manduca sexta* shown here). Each segment contains many longitudinal and oblique muscles. **(B)** A soft silicone-elastomer robot (GoQbot) that mimics the body of *Manduca* with paired longitudinal shape–memory alloy (SMA) coil actuators. **(C)** Rapid ballistic rolling that exploits the morphability and elastic storage of a soft body, achieved by coordinated contraction of SMAs.

locomotion. Grip release must therefore be completely reliable regardless of the shape or texture of the substrate. It is unlikely that the retractor muscles are controlled with great precision or adjusted with every step to compensate for changes in attachment. It is more likely that very soft parts of the proleg are deformed to redirect automatically muscle forces to ensure hook release from the substrate. The system appears to be an excellent example of morphological computation and illustrates how important the embodiment process will be in the design of soft robots [1].

These caterpillar-like robots demonstrate an important attribute of highly deformable devices: they can morph to exploit other body shapes. As an example, the GoQBot (Figure 3B) has an elongated narrow body that can be deformed into a circle. When done quickly, this change releases enough stored elastic energy to produce ballistic rolling locomotion (Figure 3C) [8]. The GoQBot changes conformation within 100 ms, generating approximately 1 G acceleration and 200 rpm, enough to propel the 10-cm-long robot at a linear velocity of 200 cm/s.

### *Octopus and octopus-like robots*

Some of the most elaborate and intricate soft-bodied movements are accomplished by cephalopods (e.g., octopus and squid). Cephalopods can change their shape to mimic the environment or other animals, and they can deform their bodies to fill completely, for example, a cubic box. This remarkable physical fluidity, together with an ability to manipulate objects, has made the octopus an attractive model [28].

Each octopus arm is packed with muscles organized into distinct anatomical groups [29,30]. A central block of transverse muscle sends fibers peripherally to interdigitate with bundles of longitudinal muscle fibers. Both are surrounded by three sets of oblique muscle layers that spiral in left and right helices along the length of the arm. The arm articulates the shape by shortening, elongation, bending, or torsion, and forces can be distributed by localized or global stiffening [30]. Muscle tissues maintain a constant volume, which allows the octopus to exploit the hydrostatic exchange of displacement and force. By stereotypical movements, it has been shown that octopuses can simplify control by reducing the degrees of freedom. For example, in a behavior called 'arm reaching', a wave of stiffening and straightening forms a propagating passive bend [31–33]. Similarly, localized bending of the arm (pseudojoints) can be seen in some forms of fetching movement [32,34]. However, the extraordinary intricacy of most octopus movements [35,36] cannot be explained by such stereotyped movements alone but presumably involves local control by the 50 million peripheral neurons within each octopus arm [33,37].

A variety of octopus-inspired robots have been developed, mostly using the broad concept of compartmentalized deformation to produce limbed locomotion [38,39]. Some solutions for soft manipulators, such as the OctArm robot, use pneumatic muscles that can bend in all directions [2]. The pneumatic approach is used in walking robots composed of layers of silicone elastomers containing embedded channels that can be pressurized by fluid or air. Through careful design of chamber size, wall thickness, and geometry, selective inflation and deflation of these cavities can produce a variety of walking gaits [39]. With the development of pumps, valves, and power supplies that are compatible with highly deformable body structures, it will be possible to construct extremely intricate embedded pneumatic networks capable of high-resolution, complex movements.

Another approach for a completely soft manipulator is based more directly on the anatomy and mechanisms of octopus arm movements [40,41], specifically on the imitation of the longitudinal and transverse arrangement of soft actuators, as in muscular hydrostats [42,43]. A plastic fiber braid constitutes the highly deformable mechanical structure of this robot arm [7], whereas soft actuators comprised of SMA springs [44] are arranged transversely and longitudinally to produce the local deformations [45] shown in Figure 4. Global bending is obtained with longitudinal cables. The arm works in water, exploiting the interaction with the environment, as observed in the animal model,

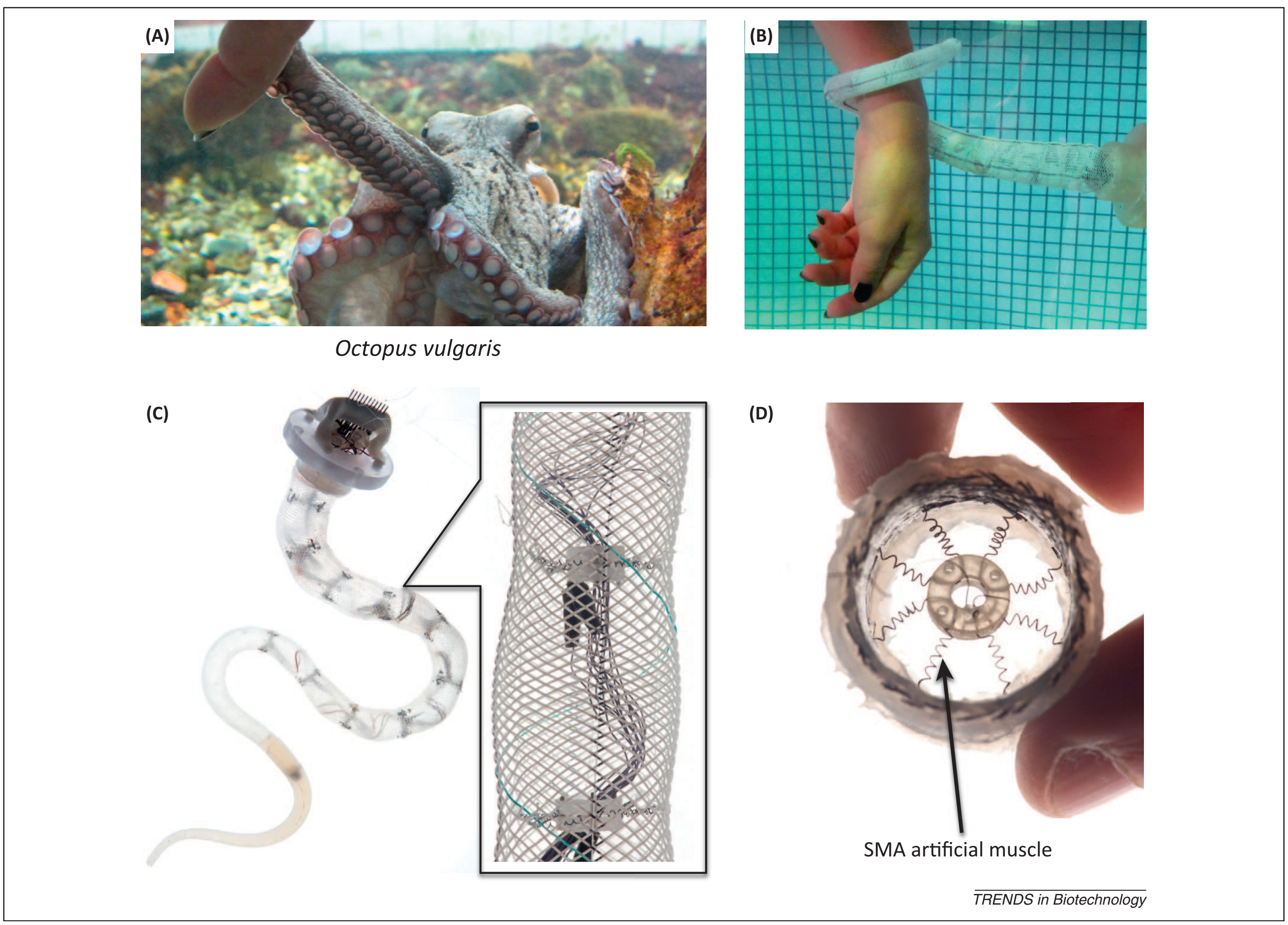


**Figure 4.** Octopus-inspired robot. **(A)** Octopus (*Octopus vulgaris*) grasping a human finger with one arm. **(B)** An octopus-like robot arm wrapping around a human wrist, in water. **(C)** Details of an octopus-like robot arm. The external braid represent the mechanical structure of the arm, allowing for local and global deformations while keeping the arm shape (reproduced with permission from Massimo Brega, The Lighthouse). **(D)** Details of the SMA springs that generate local diameter reductions (reproduced with permission from Massimo Brega, The Lighthouse).

and can elongate, shorten, bend, and stiffen. A similar approach, but using silicone and cables, has led to the first soft robot with both manipulation and locomotion capabilities [46]. In this case, the octopus locomotion strategy in water has been synthesized and applied in the design of the robot. It consists of pushing with the rear arms, which is achieved by exploiting the effect of water on gravity, the shortening/elongation functions of the arm, the adhesion of the arms to the substrate, and the ability to stiffen parts of the arms. The result is a six-limbed robot capable of both locomotion in water and grasping objects by wrapping one limb around them.

## Soft technologies in robotics and challenges

### *Actuation*

One of the biggest challenges in soft robotics is designing flexible actuation systems capable of high forces, to replicate the functionality of muscles in the animal body. The ability of soft animals to change body shape depends on a large number of muscles being distributed over the body. Currently there are three popular actuation techniques.

The first technique is to use dielectric elastomeric actuators (DEAs) made of soft materials that actuate through electrostatic forces – an important development in the quest for artificial muscles [47,48]. Despite its relatively high performance metric (high strain/stress and mass-specific power), this technique has limitations. (i) Most designs that use DEAs require a rigid frame that prestrains the elastomer. A few designs work without rigid frames, but they yield very low stress, and their fabrication process is complex [49]. (ii) The reliability of the compliant electrodes used in these designs needs improvement. (iii) The technique requires high voltages, which is undesirable for many applications.

The second technique is to use SMAs, which are popular choices for soft actuation due to their high mass-specific force. Because the strain is relatively low (~5%) in the most common nickel–titanium alloys, engineers often create coils from a thin wire to amplify the overall strain [8,42,50]. This allows SMAs to be formed into highly flexible threadlike springs that can be integrated into a soft structure. However, force generation in SMAs depends on temperature change, so robust temperature control in various thermal conditions is a challenge. The most input energy is consumed by heating SMA wire itself, therefore, efficiency is very poor (~1%). Moreover, overheating or overstraining can easily cause permanent damage to the actuator.

The third technique is to use compressed air and pressurized fluids. This technique has provided powerful actuation systems for soft materials since the 1950s. Contractile devices such as McKibben actuators (made of a fiber braid) that are deformed by pressurized air can produce relatively high forces and displacements, but they require high power and complex compressed air supply systems. However, a soft orthotic device that uses pneumatic actuators has recently been developed using this technique [51]. Alternatively, compressed air and fluid can deform soft body parts directly using networks of channels in elastomers to inflate chambers and create motion in tethered robots [39]. Such a hydraulic network was used to change the skin color of a soft robot, mimicking animal camouflage strategies [52].

### *Stiffness modulation*

A critical technology for soft robotics is stiffness modulation. Soft systems need stiffness in order to apply intentional forces to a specific task, such as tissue sampling. Soft robotics technologies have looked to animal models for ways to vary body stiffness as needed for a given task. For example, muscles transition from a passive (low stiffness) to an active (high stiffness) state [53]. This property is used not only for actuation but also to help distribute forces or to dissipate energy to maintain stable locomotion [54]. An interesting example of variable stiffness is a soft gripper based on particle jamming [55,56]. Granular material is loosely enclosed in a sac to create a soft and flexible structure that can conform to the shape of objects that it is pressed against. After the sac conforms to an object, pressure inside the sac is reduced with a vacuum pump, causing the granular filling to pack firmly to create a stiff structure that can grasp the object with relatively low applied force. A similar idea has been implemented in a laminated tubular structure to create a variable-stiffness tube for laparoscopic applications [57]. The pneumatic network architecture used for this structure modulates stiffness by controlling the pressure of compressed air [39].

### *Soft materials*

Although conventional rigid robots articulate discrete joints that are designed to have negligible impedance, soft robots articulate their entire body structure as a continuum. To minimize the force required to cause deformation, the body should be made of low-modulus materials (such as elastomers). Silicone rubber is a popular choice for body fabrication due to its availability in low modulus (as low as 05-00 durometer) that allows high strain and the convenience of a room-temperature vulcanizing process. It is also a good biocompatible material for medical applications. For future alternative material choice, a recently developed tough and highly stretchable hydrogel [58] can serve as a soft body material that may integrate tissue-engineered materials by providing scaffolding. Dissolvable robots made of soft, biodegradable materials could be used to deliver drugs to specific tissues [59].

New techniques are needed to model and control the environmental interactions of soft-bodied robots. Known robotics techniques for kinematic and dynamic modeling cannot be directly used in soft robotics because the structure is a continuum and deformation is highly nonlinear owing to large strain. Several constitutive models for large deformations of rubber-like materials have been developed [60,61], but soft robots usually have heterogeneous structures with complex boundary conditions, so accurate dynamic modeling of such systems is still challenging. Most current approaches for modeling direct-continuum materials in soft robotics are limited to kinematic analysis [62,63].

## Future convergence with tissue engineering

Soft materials open up new prospects for bioengineered and biohybrid devices [64]. Researchers have created a flexible biohybrid microsystem that models the alveolus–capillary interface of the human lung [65]. A soft material allows the interface to be rhythmically stretched, reproducing the cyclical mechanical effects of breathing. By growing cardiac muscle cells, researchers have developed a tissue-engineered jellyfish that can swim [66]. Significant advances have been made in developing biomaterials suitable for minimally invasive surgery (MIS) soft robots, such as soft, transient electronics [67] and a tissue growth scaffold made from biopolymers such as silk. A locomotive 'bio-robot' is fabricated by growing muscle cells on a 3D printed hydrogel structure [68]. A soft robot could be designed with biomaterials that release therapeutic agents locally [69] or that deposit materials that the body can use as a scaffold for tissue repair [70].

Soft robots built from biological materials and living cells would inherit the advantages of these materials: they have extraordinary potential for self assembly (from molecular structures to integrated devices); they are powered by energy-dense, safe, hydrocarbons such as lipids and sugars; and they are biocompatible and biodegradable, making them a potentially green technology. The primary robotic components needed are: (i) actuators (synthetic or living muscles); (ii) a mobile body structure (built from biopolymers in any desired configuration); and (iii) a supply of biofuel (e.g., mobilizing glucose or lipid reserves in the body cells of the robot). Such robots could be built (or grown) by using parallel fabrication methods, therefore, they also have great potential for tasks that require disposable devices or swarm-like interactions. New challenges lie in the selection of appropriate tissue sources and in interfacing them with synthetic materials and electronics.

## Concluding remarks

Recent work on soft technologies embodied in robotic systems has been greatly inspired by the study of soft-bodied animals. The investigation of biological examples is playing a vital role in developing new robotic mechanisms, actuation techniques, and algorithms. To construct robots that implement the biomechanical intelligence of soft-bodied animals, we need new active soft materials. Developing soft muscle-like actuation technology is still one of the major challenges in the creation of fully soft-bodied robots that can move, deform their body, and modulate body stiffness.

Soft technologies will greatly assist the development of robots capable of substantial interaction with an environment or human users by providing: (i) safer and more robust interactions than are currently available with conventional robotics; (ii) adaptive behaviors that use mechanical intelligence and therefore simplify the controllers needed for physical interaction; and (iii) cheaper and simpler robotic components. Soft robotics has particular utility for medical applications. Soft materials may enable robotic devices that are safe for use in medical interventions, including diagnosis, drug therapy, and surgery. For example, soft robotics may expedite the development of MIS techniques. A soft-bodied MIS robot might cause less tissue trauma than rigid instruments during insertion and navigation through soft tissues and complex organ geometries. In the near future, we will be able to engineer biohybrid soft robotic systems for medical interventions by combining biocompatible soft materials and tissue-engineered cells.

The applications of soft robotics will drive the convergence of technologies. To create a generation of soft robots in real-world situations requires seamless integration of various disparate fields such as mechanical, electrical, bioengineering, material science, and medicine. We envision that such technological convergence eventually allows for prosthetic limbs and organs that consist of artificial robotic components and tissue engineered materials.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tibtech.2013.03.002.

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